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MICROSCOPIC RELATIONS OF MAGNETITE, HEMATITE, PYRITE AND CHALCOPYRITE.

F. N. GUILD.

IN the evolution of igneous rocks, magnetite-chalcopyrite formations resulting from some of the earlier differentiation activities leading to ore deposits constitute a type of mineralization of more than ordinary interest. One reason for this is that they approach the magmatic stage closer than some others more frequently studied and clearer in their microscopic relations. Then too, these deposits raise the question of the relation of magnetite and hematite, martitization, and similar features concerning which more data are desirable. It would seem from an examination of the literature that magnetite and hematite undergo similar transformations whether found as contact deposits, metamorphic sediments, veindikes, or magmatic ores. It might be mentioned here that probably the distinction between these types has been too greatly emphasized. If deposited first as hematite it may be reduced to magnetite; if deposited as magnetite it may oxidize to hematite. Indeed, a third transformation may take place which is a reversal of one of those mentioned above. The alteration of hematite to magnetite is probably always hypogene but the reverse transformation, although commonly hypogene, may at times be supergene. Magnetite is probably not formed by supergene activities.

The present paper deals mainly with the typical contact ore deposits in which the sulphides are an important feature, but

since, as mentioned above, similar alterations of the oxides of iron take place in all, a brief summary will be given of the views held by various writers regarding this point. The material described in this investigation is confined to three localities: (1) the San Xavier district, located about twenty miles south of Tucson, Arizona; (2) the Twin Buttes district, about six miles farther south in the same range of mountains; and (3) the Pontatoc mine, a small isolated deposit on the south slope of the Catalina mountains about ten miles north of Tucson.

According to Chas. F. Park,[1] the oldest observed rock in the district is a pre-Cambrian granite that makes up the greater portion of the Sierrita range in which the mines are located. The limestones permitting classification are Permian and are mingled with beds of quartzite, shale, gypsum and some conglomerate. The sedimentary rocks are intruded by a dark dioritic rock. The ore deposits are in the Permian limestone. The ore appears to have come from an intrusive rock at shallow depths, all rocks, independent of their character, having been mineralized. In the Twin Buttes district the rocks consist of limestone marbleized and garnetized as in the San Xavier formation. The main igneous mass is a granite with "remnants of older diabase." The ores are along the contact of this igneous mass and the limestone.[2] The Pontatoc mine seems to consist of a very limited deposit of chalcopyrite and hematite in an epidote gangue with practically no pyrite or other ore minerals. It represents a limited mineralization in the great mass of Catalina gneisses associated with limestone.

As to the immediate source of the magnetite or hematite in deposits of this type, it has frequently been suggested (1) that the ferromagnesian silicates of the igneous rocks brought in contact with limestone gave rise to lime silicates permitting the excess of iron in the basic silicates to separate out and recrystallize as magnetite or hematite; (2) that the sediments may have

[1] Park, Chas. F.: Geology of the San Xavier District. Manuscript, Univ. of Ariz. Library, 1929.

[2] Gordon, E. R.: Geology of the Twin Buttes Mining District. Manuscript, Univ. of Ariz. Library, 1922.

contained much iron either in the form of the oxide or sideritic material in the limestone; and (3) that hydrothermal or pneumatolytic solutions may have brought them in from the magma where they had separated by magmatic differentiation. However they may have been formed originally, it would seem clear that they have been considerably worked over and concentrated by solutions or solvents from the magma. They may even be injected, if the geological conditions are favorable, in the form of what have been called vein-dikes. These hydrothermal solutions might so thoroughly work over the contact material that practically a new magma is developed in which magmatic phenomena of differentiation begin anew. Magnetite in pegmatite has frequently been described. Grout [3] finds magnetite present to the extent of 10 per cent. in otherwise normal granite associated with pegmatitic material. The larger deposits of the district are in pegmatites in shattered schists and granulites with biotite. Magnetite, wherever formed, is probably crystallized from deep-seated (pneumatolytic) solutions, and the particular type of the deposit depends upon the amount of the solvent and its ability to migrate. That magnetite does not oftener occur in pegmatites is probably due to the ease with which the oxide of iron, especially in the ferrous state, enters into complex silicates either before reaching the pegmatite or even later, where it may enter such typical pegmatite minerals as tourmalin or wolframite. The deposits of both Twin Buttes and San Xavier contain small amounts of molybdenite, thus relating them to this type of activity. Then again, what have been termed true dikes of practically pure magnetite have been described by some writers.[4]

It is noticeable that in contact deposits containing the oxide of iron as a mineral, quite pure hematite is in some cases formed as the primary mineral, whereas in others it is magnetite. It has been found in hydrothermal experiments in the laboratory that ferric salts in solution may yield synthetic hematite, whereas

[3] Grout, F. F.: Magnetite Pegmatites of Northern Minnesota. ECON. GEOL., vol. 18, p. 253, 1923.

[4] Alling, H. L. (quoting Miller): Genesis of the Adirondack Magnetites. ECON. GEOL., vol. 20, p. 345, 1925.

ferrous salts yield magnetite. This may be a clue to the explanation of the formation of hematite in some places, and magnetite in others, as the primary oxide. Hematite forms when ferric sillicates are present in the raw material but magnetite is formed when siderite (a ferrous salt) or other ferrous minerals are present either in the sediments or the igneous body.[5] Of course the oxidizing or reducing effect may also have been a function of the emanating magmatic solutions as well as the raw material. The formation of magnetite in complex silicate melts such as smelter slags is well known. Some complex iron silicates, such as acmite, yield magnetite by simple melting. The separation in slags is in the form of the lower oxide,[6] as would be expected, since the reducing conditions of the furnaces are the natural result of the presence of carbon and sulphur in the furnace gases. According to B. S. Butler,[7] ore solutions coming from a magma would pass through a zone rich in carbon dioxide from the limestone, and with favorable temperature the ferrous oxides of the solutions would be oxidized (by CO_2) and deposited as ferric minerals or hematite. Although Butler does not discuss particularly the relation of magnetite to hematite, he does add, however, that as the solutions rise still higher there would be a greater concentration of CO (from CO_2) and the reaction would be reversed. Applying this to the magnetite-hematite problem, magnetite might be formed under magmatic conditions, oxidized at considerable depths by carbon dioxide to hematite, and reduced again to magnetite at shallower depths. Martitization (a further change back to hematite) might proceed at still higher levels, perhaps even in the supergene areas. It has generally been thought that magmatic solutions are reducing. This may not be the case if conditions are correct for carbon dioxide or even water to act as an oxidizing agent. Lasky[8] doubts the ability of CO_2

[5] Behrend und Berg: Chemische Geologie, Stuttgart, 1927, p. 167, quoting Kuhara: Experiments on the Hydrothermal Precipitation of Magnetite and Hematite, Jap. Jour. Geol. and Geog., IV, p. 1.

[6] Perhaps the term lower oxide is inappropriate, as magnetite is a true spinel.

[7] Butler, B. S.: A Suggested Explanation of the High Ferric Content of Limestone Contact Zones. ECON. GEOL., vol. 18, p. 398, 1923.

[8] Lasky, S. G.: The Systems Iron Oxides: CO_2: CO, and Iron Oxides: H_2O: H_2, as Applied to Limestone Contact Deposits. ECON. GEOL., vol. 26, p. 485, 1931.

to oxidize magnetite to hematite. He considers the problem from the standpoint of equilibrium in the gas-solid system, and from this viewpoint questions its value in the realm of geological application. From similar considerations water as an oxidation agent for the same reaction is considered inadequate. "A volume of $CaCO_3$ 200,000 times as great as that of the hematite is necessary to produce sufficient CO_2 to form that hematite from magnetite at 500° C."

Textures have frequently been described which show quite conclusively that hematite in nature does alter to magnetite. Thus Gruner [9] has suggested that some of the material studied by him in Minnesota had originally formed as hematite, then altered to magnetite and later still had oxidized back to hematite. Ramdohr [10] has later described the same sequences. He shows photomicrographs of material from Chile consisting of the characteristic laminæ of hematite but mingled with a few laminæ of magnetite of identical shape. These he considers to have been derived from hematite. Incipient alteration back to hematite is also shown in the illustrations. According to Osborne [11] magnetite laminæ replacing calcite, on etching with HCl, develop aggregates of magnetite grains of varying orientation. This was thought to suggest that the magnetite was pseudomorphic after the earlier deposited hematite. These sequences are plainly illustrated in Figs. 9–11. Fig. 9 shows laminæ of hematite completely altered to magnetite along the outer borders of the divergent groups. Fig. 10*a* shows the more common type of alternating laths of hematite and magnetite. Here the relation is not so plain, but in Fig. 10*b* the later character of the magnetite is even more apparent than in Fig. 9. The original laminæ of hematite have been fractured and magnetite has formed surrounding or replacing the borders of the fragments. Fig. 11

[9] Gruner, J. W.: Paragenesis of the Martite Ore Bodies and Magnetite of the Mesabi Range. ECON. GEOL., vol. 17, p. 1, 1922.

[10] Ramdohr, P.: Beobachtungen an Magnetit, Ilmenit, Eisenglanz und Ueberlegungen über das System FeO, Fe_2O_3, TiO_2. Festschrift zur 150-Jahrfeier der Bergakademie Clausthal, 1925.

[11] Osborne, F. F.: A Diabase Contact-metamorphic Mineral Deposit in Ontario. ECON. GEOL., vol. 24, p. 727, 1929.

(oil immersion) is thought to represent the later reversion to hematite which has taken place in the interior of the crystals as well as in borders.

Gilbert[12] has discussed magnetite under two types, the one older than hematite and the other younger. The older is in equidemensional grains, commonly cracked and replaced by hematite along the borders and in the fractures. The hematite may or may not be oriented with reference to the octahedral planes of the magnetite. When oriented, it may take the form of parallel plates running in several directions in the magnetite. Although this texture is similar in appearance to the intergrowths found in titaniferous iron ores usually held to be due to unmixing, it is here thought to be a true replacement. Magnetite later than hematite is laminated in texture, in fact it has inherited this structure from the earlier specularite. When not completely replaced, the later magnetite appears as streaks parallel to the elongation of the laths. These relations are again brought out in the preceding paragraph and the sequences made clearer by Figs. 9–11.

As to the formation of late hematite from magnetite, Alling[13] looks upon the development of martite in certain Adirondack deposits as a deep-seated condition rather than surface oxidation. In fact he objects to the "oxidation theory as unnecessary and inadequate." "The martite is considered to have been derived from a basic differentiation of the syenite-granite magma." It is a "late magmatic introduced mineral which replaced the previously deposited magnetite" (p. 354). On the other hand the martitization of magnetite in certain sideritic ores of the Marquette district of Michigan is considered by Weinert[14] to have proceeded from the surface of the ore body downward and to have been caused by descending solutions. Per Geijer[15] had already expressed his opinion that the tendency to ascribe the

[12] Gilbert, G.: Some Magnetite-Hematite Relations. ECON. GEOL., Vol. 20, p. 587, 1925.

[13] Alling, H. L.: *Op. cit.*, p. 335.

[14] Weinert, F.: Martite and Other Iron Oxides in the Marquette District, Michigan. ECON. GEOL., vol. 28, p. 68, 1933.

[15] Geijer, Per: Supergene Martite. ECON. GEOL., vol. 26, p. 437, 1931.

martitization of magnetite to ascending solutions may have been over-emphasized. In studying the weathered magnetite bodies of Central Sweden, he finds that the alteration has been of two types; (1) the formation of siderite, partly colloform and mainly by replacement of limestone gangue in the magnetite ore, and (2) the oxidization of the siderite to limonite and the magnetite to martite and limonite. The ore is well exposed through mine operations and the lower parts show no martitization.

Gruner [16] finds that magnetite in the laboratory oxidizes to hematite at 150° C., and that the oxidation always takes place along octahedral planes, a fact for which he finds explanation in the x-ray structure of these minerals. His experiments were on polished surfaces and lasted up to 330 days. Martite, regardless of origin, has the same internal structure as hematite. Later [17] he found that, in the laboratory, minerals may be oxidized by water or steam at temperatures near 260° C. These experiments were thought to lend support to the opinion that the Lake Superior hematite-limonite ores were oxidized and leached hydrothermally.

In the oxidation of magnetite, it would seem that under certain conditions a dimorphous form of hematite is developed. This has been variously called oxidized magnetite, magnetic hematite, ferromagnetic ferric oxide, and maghemite. Sosman and Posnjak [18] found that Fe_2O_3 can exist in two forms at atmospheric temperatures, (1) hematite which is paramagnetic, and (2) a less known type which is ferromagnetic like magnetite or iron. According to these authors ferromagnetic Fe_2O_3 has been known for 60 years, little having been done in the investigation of its properties. It was first noted by Robbins [19] in 1859. Later it was observed as a product in the rusting of iron. The natural specimen [20] investigated by Sosman and Posnjak was from a

[16] Gruner, J. W.: Magnetite-Martite-Hematite. ECON. GEOL., vol. 21, p. 375, 1926.

[17] ECON. GEOL., vol. 25, p. 697; *idem.*, p. 837, 1930.

[18] Sosman and Posnjak: Ferromagnetic Ferric Oxide, Artificial and Natural. Jour. Wash. Acad. Sci., 15, p. 329, 1925.

[19] Robbins: Magnetic Peroxide of Iron. Chem. News, I, 11–12, 1859. (Quotation from Sosman's paper.)

[20] Collected by L. C. Graton and B. S. Butler.

gossan deposit from Iron Mountain, Shasta Co., California, and contained only 2.40% FeO. Sosman suggested that a new name should be given the natural product but thought it better to wait until purer material had been collected and examined. X-ray examination proves it to have the same structure as magnetite. This, according to Sosman, is the second case in which two compounds of different composition and physical properties have the same x-ray structure. Goethite by dehydration yields hematite while lepidocrocite, a dimorphous form of goethite, yields the magnetic product. Newhouse and Callahan[21] have studied material supposedly of the same type from a variety of localities. One occurrence, that from Cornwall, Penn., suggests its formation by hypogene solutions. Wagner[22] also finds this product abundant as a mineral in South Africa. He even finds that in some of the most strongly magnetic varieties of the ore, magnetite is absent, its place being taken by a strong magnetic form of ferric oxide that, except for the color of the powder, has all the

FIG. 1. Primary magnetite, *i.e.*, not pseudomorphous after hematite, replaced by chalcopyrite (white). Black is mainly silicates. Twin Buttes, Arizona. × 45.

FIG. 2. Magnetite, also primary, replaced by pyrite (white). Pyrite is surrounding equidimensional grains of magnetite. Gray surfaces are magnetite. Twin Buttes, Ariz. × 100.

FIG. 3. Secondary magnetite (dark strips) pseudomorphic after hematite replaced by pyrite (light). Veinlet of quartz (black) crossing the slide. San Xavier mine, Ariz. × 45.

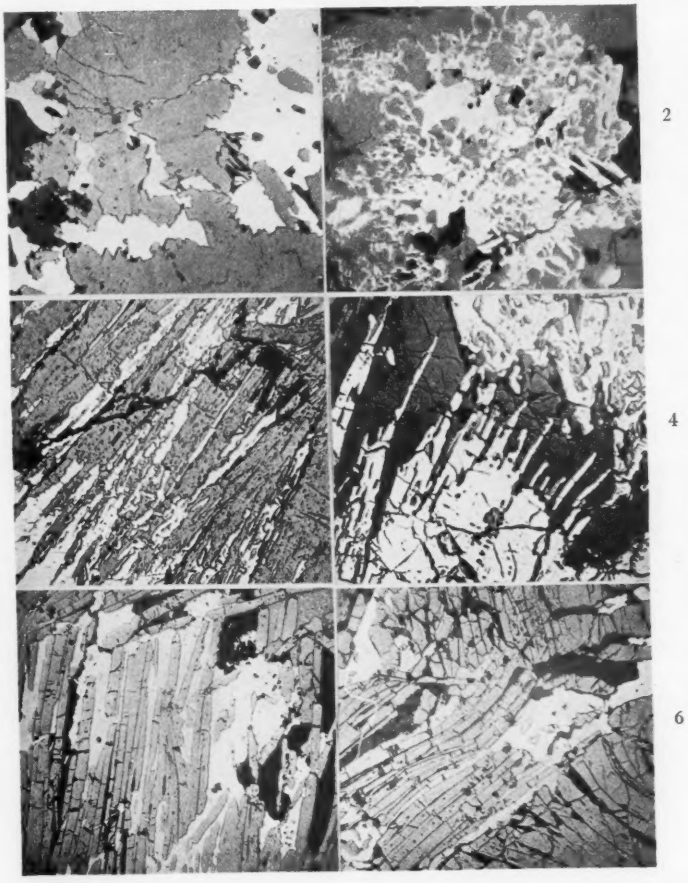
FIG. 4. Laminated pyrite (white) showing texture inherited from replaced magnetite which has inherited its texture from hematite. Quartz, nearly black; magnetite, dark gray, appearing mainly as spots in the pyrite. San Xavier mine, Ariz. × 45.

FIG. 5. Laminated magnetite (dark gray) replaced by chalcopyrite (white). A small area of interstitial sphalerite shows dots of chalcopyrite. San Xavier mine, Ariz. × 52.

FIG. 6. Laminated magnetite (dark gray) replaced by chalcopyrite (white) and quartz (nearly black). San Xavier mine, Ariz. × 35.

[21] Newhouse, W. H., and Callahan, W. H.: Two Kinds of Magnetite? ECON. GEOL., vol. 22, p. 629, 1927.

[22] Wagner, P. A.: Changes in the Oxidation of Iron in Magnetite. ECON. GEOL., vol. 22, p. 845, 1927.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properties of hematite. Wagner, however, suggests that it is formed by the normal atmospheric weathering of the magnetite. He has suggested the name of maghemite for this natural product. The views concerning these specific samples have been confirmed by Schneiderhöhn,[23] who adopted the name maghemite, though he thought Sosmanite would have been better. Newhouse[24] believes that lodestone is chiefly ferromagnetic ferric oxide, or oxidized magnetite (maghemite) which possesses the property of remanence to a greater degree than magnetite. Specimens studied from several localities show that the brownish oxidized magnetite may be lodestone but those not showing this characteristic are not polar. The ability to pick up nails, etc., was roughly proportional to the amount of this oxidized material.

The sulphides, pyrite and chalcopyrite, together with lesser

FIG. 7. Same as Fig. 6, but showing more detail in the replacement of magnetite by chalcopyrite. Some residual hematite may also be seen. × 110.

FIG. 8. Laminated hematite fractured and replaced by chalcopyrite. The hematite shows same laminated texture as magnetite in Figs. 5–7. Pontatoc mine, near Tucson, Ariz. × 124.

FIG. 9. Laminated hematite being replaced (reduced) by magnetite. Hematite light, magnetite darker, and holes black. The center of a radiating mass of hematite is mainly unreplaced, but the outer border is nearly pure magnetite. San Xavier mine, Ariz. × 35.

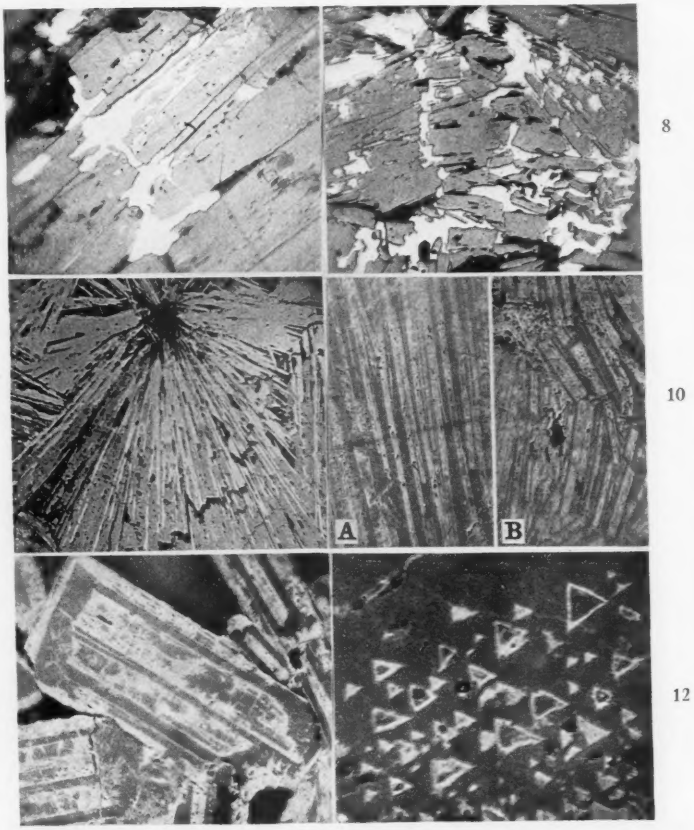
FIG. 10. Left hand portion (*A*) consists of alternate bands of hematite (light) and magnetite (darker). Right hand portion (*B*) is from same specimen and shows broken laminæ of hematite replaced and crossed by magnetite. "Magnetite" float near Pontatoc mine, Ariz. × 135.

FIG. 11. Hematite (light) and magnetite (darker) from same specimen as Fig. 10, showing complicated texture of second generation hematite, or hematite replacing magnetite pseudomorphic after hematite of the first generation. × 350 (oil).

FIG. 12. Magnetite area in same specimen illustrated in Figs. 10 and 11, but showing a replacement by second generation hematite in hollow triangular shapes. × 1200 (oil).

[23] Schneiderhöhn, H., and Ramdohr, P.: Lehrbuch der Erzmikroskopie, II., p. 535, Berlin, 1931.

[24] Newhouse, W. H.: The Identity and Genesis of Lodestone Magnetite. ECON. GEOL. vol, 24, p. 62, 1929.



7 8

9 10

11 12

amounts of sphalerite and galena observed in this investigation, are all later than magnetite or hematite even when magnetite is secondary to hematite. In Fig. 1 (Twin Buttes, Ariz.) chalcopyrite is seen to be later than a type of magnetite which does not appear to be a reduction product of hematite. This is made evident from the euhedral character of the magnetite as well as its equidimensional shapes, which are in striking contrast to laminated magnetite shown in Figs. 3, 5, 6 and 7. Hematite has not developed in this material and, in fact, is not found in appreciable amounts either as a primary mineral or alteration product of magnetite. This feature is a characteristic difference between the Twin Buttes ore and that of San Xavier, six miles farther north. No conclusive explanation of this can be made, although it should be noted that the Twin Buttes mine contains greater amounts of the heavy sulphides. Fig. 2 (also from Twin Buttes) shows pyrite replacing equidimensional (primary) magnetite, giving rise to a sort of "intergrowth" texture. Note how the pyrite wraps itself around the magnetite grains, a rather unusual habit for pyrite. This should be compared with Fig. 3, which consists of the same minerals but of quite different texture. Pyrite is replacing laminated magnetite and itself takes on a laminated texture. This is emphasized still further in Fig. 4 (San Xavier) where most of the magnetite has been removed, leaving fingers of pyrite extending into quartz. One finger of pyrite in the photomicrograph may be seen to be a continuation of a magnetite lamina.

Figs. 5, 6 and 7 show very plainly the relations of chalcopyrite to laminated magnetite in the San Xavier mine. Fig. 7 especially shows the disintegration (replacement) of individual laminæ of magnetite. Only small amounts of residual streaks of hematite are present in these specimens but may, perhaps, be observed in the reproduction (Fig. 7). The texture in Fig. 8 is identical to the last three described, but here chalcopyrite is replacing hematite instead of magnetite. This is from the Pontatoc mine north of Tucson. Specimens from this locality are not entirely free from magnetite, which when present, appears as clear-cut bands parallel

to the hematite laminæ, and occasionally as patches of irregular outline. The relations of magnetite and hematite are illustrated in Figs. 9–12. Fig. 9 shows a gradational effect from nearly pure hematite near the center of a radiating mass to nearly pure magnetite along the outer border. Fig. 10 shows the alteration of hematite perhaps more strikingly even than Fig. 9. The left hand portion (*A*) shows parallel bands of alternating hematite and magnetite so regularly arranged as to suggest contemporaneous intergrowth. The right hand portion (*B*), however, shows the laminæ of hematite greatly brecciated and the magnetite completely surrounding or replacing the fragments. Some of these same laminæ are shown under high power in Figs. 11 and 12. The complicated structure in Fig. 11 is thought to represent the secondary magnetite going over again into a second generation of hematite. Fig. 12 is an area of magnetite in which hematite of the second generation has formed in triangular designs following octahedral directions of magnetite.

Resumé.

1. Magnetite in contact deposits may be formed as a primary mineral, or pseudomorph after hematite. These two types may be easily recognized by the microscope.

2. Photomicrographs are shown illustrating the relations of magnetite and hematite. These show gradational effects so that the sequence of deposition is conclusively brought out.

3. Interesting textures showing relation of second-generation hematite and magnetite are illustrated in oil immersion photomicrographs.

4. The sulphides are all later than magnetite or hematite, and photomicrographs are included showing some of these relations. Pyrite may show an inherited texture from magnetite, but chalcopyrite does not. It is mainly interstitial with reference to both magnetite and hematite.

5. The presence of much sulphide perhaps determines the deposition of magnetite in preference to hematite. Possibly pyrite is more active in this respect than other sulphides.

6. Hematite may form as a primary mineral in the presence of a sulphide, as shown in material from the Pontatoc mine.

The photomicrographs were taken with a KM Leitz petrographic microscope fitted with a vertical illuminator and a 20 in. Korona View camera manufactured by Grundlach. Eastman process panchromatic cut films were used with Wratten ray filters. The oil immersions were taken with a 70 × fluorite objective with periplane oculars.

UNIVERSITY OF ARIZONA,
TUCSON, ARIZ.

CALCITE MARBLE.

GEO. W. BAIN.

ABSTRACT.

Thermal metamorphism of bituminous limestone to white marble by hot solutions flowing along bedding planes in the original rock is not generally recognized. Most marble deposits in North America, especially those of Vermont, indicate this to be the most important process in development of "crystalline" marbles.

Vermont calcite marble deposits extend along a zone of lower Ordovician sediments outcropping from the northwest corner of the state to the middle of the southern border. Sediments in the extreme north are dense, dark, bituminous limestones which take a high polish; in the central part of the state they are mixed white and gray marble; and in the southern region they are a coarse, compact mass of water-white calcite grains.

Coloring agents are removed from the limestone and the carbonates recrystallized for variable distances out from bands of chlorite, actinolite, and mica, which mark channels followed by hot solutions. Minor structures closed off parts of folded beds and prevented upward flow of hot solutions locally; these parts of a bed remain almost unmetamorphosed even below highly changed stone. Silicate bands remain as dolomite beds where quarrying operations follow the deposits down into structures which isolated the rock from hot solutions.

Most problems of marble as a building material are linked to this peculiar metamorphic origin.

INTRODUCTION.

MARBLE has ceased to be defined partly by composition of the material; present usage includes such a wide range of rocks as limestone and dolomite, onyx, some travertines and many serpentines. All marble will assume a highly polished surface and any one variety is composed of minerals with essentially the same hardness. It differs in this respect from most commercial granites, which are pitted where the soft minerals have been ground out during polishing, and from limestone, which is pitted

by the many pore spaces in it. I propose to confine this paper to the most common type of marble, namely calcite marble or that variety with crystals visible to the unaided eye.

I have been called upon frequently in the past eight years to make calcite marble that is young appear old; or if not that, to keep marble that wants to age rapidly in a state of perpetual youth. One marble developed a reddish coloration, in contact with alkalies, to look like a case of "measles" or "scarlet fever." I was asked to develop an antitoxin for the disease and devise a cure for those cases that had developed already. This rôle of family physician to marble has given me more than average insight into the life of the stone.

Calcite marbles are relatively soft and remarkably easy to polish. They are the most flexible building stone used, yet most commercial building varieties have a crushing strength equal to or nearly equal to that of other rocks. This flexibility of the stone is responsible for the dull resonant sound emitted when the stone is broken in contrast to the sharp cracking sound from limestone or dolomite.

Variations in calcite marble are wider in range and number than the similarities. The texture or grain size in commercial varieties varies from 0.1 to 2 millimeters, although this range goes beyond both limits in unusual orders. Vermont and other Appalachian marbles have equidimensional grains but those from Colorado have grains elongated in one general direction. Special treatment of marble during prolonged weathering occasionally brings out definite autoclastic structure in most Appalachian marbles, and great "knots" of undeformed marble remain in stone with ill-defined flow pattern. Color banding is very straight in some varieties and extremely crinkled in others. The general color of the stone varies from white to gray; white varieties may have a cream, green or pink tone in them in addition to dark green veining parallel to original bedding. Gray marble has dark markings of abnormally abundant graphite or light streaks with deficient graphite; veining, as these markings are called, may be parallel or oblique to the bedding.

General Statement or Origin.—The calcite marbles were limestones containing five per cent. or less magnesium carbonate, which have recrystallized in the presence of circulating solutions during a period of folding. Three factors are involved:

1. Original composition.
2. Circulating solutions.
3. Peculiarities of folding.

Upon these three depend most problems of the calcite marbles.

First, increase of the dolomite content to over 9 per cent.—unless the increase is to 90 per cent.—produces a stone that is difficult to polish. Recrystallization is retarded or even prevented by more than 9 per cent. dolomite, and recrystallization controls porosity and durability of the stone to a great degree. Second, color and veining are due to materials deposited or removed by circulating solutions. Third, beds of average thickness do not give the large-size blocks from which marble of uniform appearance can be sawed, and so are of no value; only where peculiarities in folding have greatly thickened a bed are commercial deposits found. The problems of architectural effect, durability, size of pieces (a sixty ton block is not unusual), and extent of deposit are all tied up with the origin of the marble.

Of all marble districts in the world, I know none equal to that in Vermont for completeness of record of the stages in forming the stone. So gradual is the change from dark bituminous limestone on Isle La Motte, to coarsely crystalline marble at Sunderland, that variation can be observed to definite degree only by examination of specimens at fifteen-mile intervals. The greatest single difference is found where the rocks change from a position below to a position above the Champlain overthrust.

GEOLOGY OF VERMONT MARBLE BELT.

The marble belt of Vermont lies in a lowland between the Green Mountains on the east and the Adirondacks on the west (Fig. 1). The Taconic Mountains fill a large part of the south end of this lowland. West of the Taconics, Lake Champlain

FIG. 1 (left). Vermont Marble Belt. Insert.—Structure, north end of Chazy beds. The only breaks in marble horizon are at Lake Champlain overthrust and at arch between Hinesburg and Taconic synclinoria.

FIG. 2 (right). Isle La Motte. Relation of beds where least metamorphosed. Gentle NW. dip, steeper adjacent to westward-dipping thrust on east shore. The Fleury bed is the equivalent of the Columbian marble, and the Fisk-Goodsill beds contain the same fossils found in the West Blue marble.

swings westward, and east of them the Green Mountains swing eastward. The lowland resembles a graben in that it is bounded on the east by discontinuous, low angle, eastward-dipping thrusts and on the west by westward-dipping thrusts extending from Canada to at least four miles south of Plattsburg. Farther south, faults are reported as eastward-dipping normal types. The rocks of the marble horizon vary from undeformed dark limestone at Plattsburg and Isle La Motte in the northwest, to white, coarsely crystalline limestone at Sunderland in the south.

Stratigraphy.—Correlation of beds across the Champlain overthrust presents numerous problems, especially because the only fossiliferous horizons are at the extreme top or extreme bottom of the sequence. Sediments near the bottom of the limestone marble deposits on Isle La Motte (Fleury quarry bed) are composed of fragments of shells rounded to calcite sand and possess crossbedded structure; this horizon lies about 200 feet above crossbedded sandy dolomite of Beekmantown age. Complete fossils are almost unknown; slight recrystallization of this crossbedded limestone, where the beds appear above the overthrust, obscures further the identity of the fossils, but a similar rock in proper sequence relative to the well known Maclurites beds above and the Beekmantown crossbedded sandy dolomite below places it as the equivalent of the Fleury quarry layer. This crossbedded limestone horizon is the Columbian marble zone of the southern section. The main Fleury quarry bed rests upon less uniform limestone, which is the Sutherland Falls marble horizon above the overthrust. The Sutherland Falls deposit keeps such constant structural characteristics that marble operators in Vermont are able to recognize every bed in its sequence from east of Burlington to East Dorset. The formations and their equivalents in the three parts of the marble belt are given in the following table.

Six of these horizons merit special comment. They are:

1. The crossbedded zone of Beekmantown sandy dolomite below which no calcite marble occurs.
2. The Sutherland Falls marble.

marble horizon are at Lake Champlain overthrust and at arch between Hinesburg and Taconic synclinoria.

FIG. 2 (right). Isle La Motte. Relation of beds where least metamorphosed. Gentle NW. dip, steeper adjacent to westward-dipping thrust on east shore. The Fleury bed is the equivalent of the Columbian marble, and the Fisk-Goodsill beds contain the same fossils found in the West Blue marble.

TABLE OF FORMATIONS.

	Isle La Motte	Milton to Middlebury	South to Manchester
	Utica shale	Utica shale & slate	Hudson River phyllite
	Trenton Ls.	Trenton Ls. & marble	Blue Marble deposit
	Black River Ls.	Black River marble	
			——Local disconformity——
		Marble & limestone	Upper West Rutland marble
Ordovician			—Disconformity(?)—
			Main West Rutland marble
	Chazy Ls.		
			West blue marble
		Columbian marble	Columbian marble
			Intermediate Ls.
		Sutherland Falls marble	Sutherland Falls marble
	Beekmantown dol.	Lower limestone	Lower limestone
		Crossbedded zone	Crossbedded zone
		Rutland dolomite *	Rutland dolomite
Cambrian		Cheshire quartzite	Cheshire quartzite
Precambrian		Mendon series	Mendon Series

* The "red sandrock," Monckton quartzite, and dolomite of Mallets Bay are facies of the Rutland dolomite. The different appearance is due partly to a greater sand content but mainly to metamorphism of the ferruginous cement of the northern beds to greenish and yellowish silicates in the southern region. The Columbian and Sutherland Falls marbles are synonymous with the lower Cambrian marble of Keith and are fossiliferous at 1¼ miles northwest of Shelburne Pond.

3. The intermediate limestone which separates the Sutherland Falls from the Columbian deposit.
4. The Columbian marble.
5. The group of least changed, fossiliferous beds lying above the Columbian deposit and below the phyllites.
6. The phyllites, above which no commercial marble occurs.

The crossbedded zone is from 10 to 300 feet thick. It is thinnest in the south and varies from almost pure quartzite to slightly sandy dolomite; beds are rarely over a foot thick. This horizon is extremely useful in identifying a regular or inverted sequence as well as in delimiting potential marble land. Sutherland Falls

marble and the lower ten to forty feet of the Columbian deposit have slightly discontinuous irregular dolomite veins. These do not cross bedding planes but vary in orientation and position within a bed. The dolomite weathers to lighter color than the calcite and appears as minute chains on surfaces. The used part of the Columbian deposit—except at the abandoned High Street and Riverside quarries—is non-dolomitic, and the principal veining of green silicate bands along the bedding is relatively straight. This marble is limited above by dolomite beds interstratified with fossiliferous blue marble.

The blue marble and dolomite between the Columbian deposit and the phyllites are the least changed members of the marble series. Locally the beds become white and the dolomite becomes recrystallized to chlorite and actinolite, and these sections are the most important sources of information on the origin of the calcite marbles. Phyllites overlying the blue marble contain no limestone beds; they have many pegmatitic quartz veins bearing albite feldspar, and these become increasingly abundant with increasing distance from the marble; general metamorphism increases in like manner. Graphite has a remarkable retarding effect upon injection-metamorphism and it is believed that the graphite removed from the limestone in making marble and deposited in the overlying slate rendered this lower phase more or less impregnable to metamorphism. The rock has irregular cleavage, with a sheen due to sericite. The rock is black adjacent to the marble, but grades into a dark-brown and even greenish-brown type distant from the contact.

Structural Units of the Marble Belt.—The marble belt is divisible into three structural units. The most northerly unit is the faulted area of unmetamorphosed sediments at Plattsburg, on Isle La Motte, and Grand Isle. The central unit, between Milton and Middlebury, is characterized by extremely fine-textured stone occurring in simple open folds between thrust faults; no marble is being produced from this section and it is extremely improbable that any will be until such time as new quarrying methods are devised. Most marble is produced from the southern unit ex-

tending from Middlebury to Manchester; the marbles are medium to coarse-grained and lie in complex flowage fold structures.

General Description of the Marbles.—The limestone marbles of Isle La Motte are sold under the trade names of "French Gray" and "Champlain Black" marble. Both stones are dark colored due to the large amount of dark brownish bitumen in them. Weathering of exposures removes the bitumen and changes the rock to blue-gray surface. French Gray marble is made of rounded fragments of sea shells, coral and algal reefs, cemented by calcite and impregnated with bitumen. Complete fossils are absent; all pores are filled. Champlain Black marble is a consolidated calcite mud containing occasional complete Maclurites shells. Some light gray limestone marble was removed from lowest Chazy beds at the Fleury quarry (Fig. 2). Light colored beds low in bitumen predominate in the lower part of the sedimentary series.

Blue-gray marbles are quarried in the southern structural unit. Coloring is not uniform; dark, irregularly parallel bands are referred to as "veining." The blue-gray color and dark veining are due to minute disseminated graphite flakes. Graphite, in veins parallel to the bedding, is recrystallized partly from original bitumen and is deposited partly by circulating solutions. Graphite in veining oblique to the bedding is introduced.

White calcite marbles also come from the southern structural unit. Some are entirely white but the white beds are separated from one another or are characterized by irregular green silicate bands approximately parallel to the original bedding. A few white marbles have a secondary veining of gray dolomite mottling between the principal veining.

ORIGIN OF THE CALCITE MARBLE.

Origin of calcite marble treats first with the change of the bituminous limestone to coarsely crystalline graphitic marble, and second with the increase of graphite in the blue marble and decrease in the white marble over the average derived by recrystallization. Original differences of material, differences in degree

of recrystallization and in intensity of thermal action, are the principal influences upon origin of marble and the resultant type.

Effect of Original Differences.—The lower Chazy beds on Isle La Motte, Grand Isle and at Plattsburg differ from the upper ones in at least two ways and both affect materially the metamorphic equivalents. The lower beds in and near the Fleury quarry zone contain very little bitumen and the upper ones in the Fisk-Goodsill quarry horizon are rich in this material. Recrystallization of the beds of the Fleury quarry zone and of those immediately above give the light colored marbles of the Sutherland Falls and Columbian deposits. In contrast, the highly bituminous limestones in the upper part of the Fisk and Goodsill quarries become metamorphosed to the Blue and West Blue marble deposits in the southern structural unit.

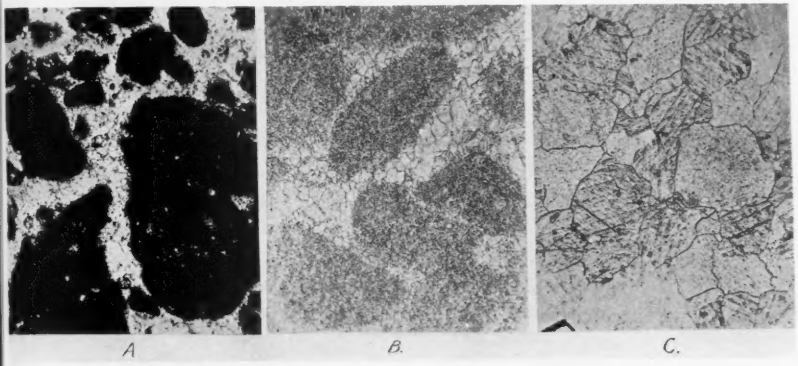


FIG. 3. Photomicrographs showing progressive stages in recrystallization of pure limestone to marble. *A*, French Gray marble, Goodsill quarry, Isle La Motte, made of bitumenized shell fragments (black) cemented by fine calcite with sharp boundary between cement and fragments. *B*, Porcellaneous marble, 1¼ miles NW. of Shelburne Pond. Similar to *A*. The crystals of the cement are visible under the microscope and interlock with the fragments they hold together. Fragments remain fine-grained. *C*, Top White marble, Covered quarry, West Rutland. The entire rock has recrystallized to a coarse mass of interlocking crystals. A few areas of smaller crystals suggest the extent of former fragments.

The lower Chazy beds are fragmental, with much lime mud and calcite cement binding the rounded fragments together (Fig. 3-A). The upper Chazy beds on Isle La Motte are about 25 per cent. algal, coral, and bryozoan reefs. Recrystallization in the marble belt affects the cement more readily than the fragments (Fig. 3-B), and likewise the fragments more readily than the reef deposits, and large masses of colonial coral have been found in the upper blue marble as far south as West Rutland. The upper blue marble or coral-bearing section is changed nowhere as much or as uniformly as the lower fragmental part of the Chazy beds because of the resistance of some of these reefs and large fragments to recrystallization.

Some beds on Isle La Motte have been dolomitized. Change in beds below the Fleury quarry zone is much more complete and uniform than higher in the series. Recrystallization of limestone to calcite marble has not been observed in this marble belt where the magnesium carbonate content exceeds 4 per cent. Beds with more magnesium carbonate, such as the intermediate and lower limestones, have remained fine-grained even adjacent to the coarse-textured but purer Sutherland Falls marble.

Effect of Recrystallization Processes.—Change of bitumen to graphite, greater ease of recrystallization of cement over fragments and the retarding effect of dolomite, are some recrystallization effects described already as related to original differences of material. Most other differences resulting from recrystallization are unrelated to original differences in the rock and are due to local variation in intensity of metamorphic activity. Probably the most outstanding persistent change is the coarsening of texture of the stone as the deposits are followed southward from Burlington. Columbian and Sutherland Falls marbles are extremely fine-textured, porcellaneous rocks east of Burlington; they are almost glassy in appearance and break with conchoidal fracture. They are fine-textured at New Haven and Middlebury; although no crystals are evident to the unaided eye, the rocks have a crystalline appearance. Individual crystals of calcite are visible to the unaided eye at few localities north of Salisbury and generally are visible at all places farther south.

Marble from the Columbian deposit at the Danby quarries is so coarse that it is used for building and large sized monuments only; the large crystals show up in small highly finished pieces. Marble from farther north at West Rutland and Pittsford Valley or from higher in the stratigraphic sequence, as at the Brook quarries, Danby, is finer textured and is substituted in all small pieces.

Two other changes follow this southward increase in intensity of recrystallization. I know of no overturned folds in the lower limestone north of the New Haven River. From this place south, folds with the steep limb overturned 30° past the vertical are frequent, and abnormally coarse textures occur where overturning approaches 90° past the vertical. Bedded veining in the marble zone at Hinesburg and farther north is remarkably straight and the marble has an open fracture system or fractures filled with coarse-textured calcite veins. This fracture system cannot be recognized south of Middlebury, and beyond Brandon flowage structures are the only ones in marble that are contemporaneous with metamorphism. Dolomite remains competent as far south as Manchester and fractures rather than flows. The open fractures in marble of the northern district indicate a very light cover during folding and metamorphism; flowage structures in the south point to a plastic condition due to great thickness of superjacent rock.

Association of abnormally coarse texture with high local intensity of folding is illustrated by the Pittsford Valley, West Rutland and Danby deposits. The Brandon Italian marble beds on the west side of the Pittsford Valley quarries (Fig. 4) have a typical grain size of about 0.2 mm. The beds are thickened from 10 feet to 132 feet on a flowage fold in Pittsford Valley quarry No. 7 and the grain size increases to 0.5 mm. The Main West Rutland deposit is thickened greatly on a flowage fold in the Covered quarry where the Rutland Italian marble bed is 11 feet thick; the rock has 45 grains per square millimeter and some are very large in contrast to the others. Thickening diminishes where the deposit is followed down the dip in the Main and

FIG. 4. Map of Pittsford Valley quarries, showing large flowage fold at north end of the deposit. The *G'* and *H* beds are unsilicated dolomite where the deposit is thinned up on the east (near) side of No. 8 prospect. The inset above shows the relative position of the Pittsford Valley quarries.

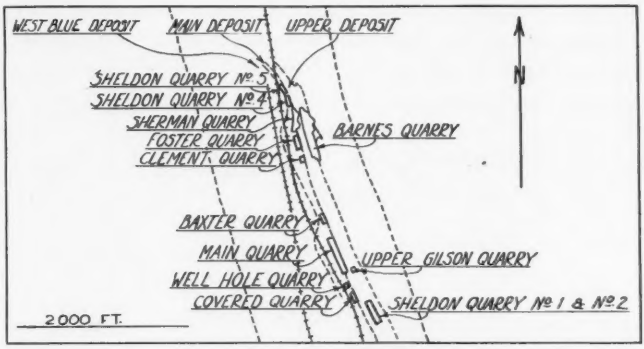


FIG. 5. Map showing the location of the West Rutland quarries, north of the town. No quarries are operating on the upper deposit; those north of the Baxter have been worked out. The Sherman was pumped out in 1931 and studied geologically. This opening and the McGarry quarry are the most significant in the series.

Baxter quarries (Fig. 5) to beyond the limit of the flowage fold. The rock has 70 grains per square millimeter, and all are of one size where the Rutland Italian bed is 4.5 feet thick at the northwest corner of the Baxter quarry. Similar changes occur in the Sherman quarry at the north end of the Main West Rutland deposit. The Columbian deposit is approximately 500 feet thick at the Imperial Tunnel quarry at Danby. This quarry is opened on a syncline on the east side of Dorset Mountain; this main structure has many small flowage folds facing the synclinal axis (Fig. 6). The marble continues around the north slope of the mountain but thins to less than 100 feet. The grain size in the quarry is about one millimeter but in the thin beds is one-half millimeter or less.

Effect of Silication Processes.—Silication accompanied metamorphism of limestone to calcite marble at Pittsford Valley, West Rutland and Danby. The general change is probably widespread, but at these places intermediate stages are exposed advantageously for study. The silicates in each deposit include chlorite, muscovite and actinolite and they occur as green streaks

or layers parallel to the original bedding. Orthoclase is disseminated through at least one white marble at West Rutland.

The beds in the Pittsford Valley deposit are designated by letter, beginning with " A " in the eastern or oldest beds quarried and lettering them consecutively to " W "; beyond " W " lies the Brandon Italian deposit (Fig. 4). Marble was found east of

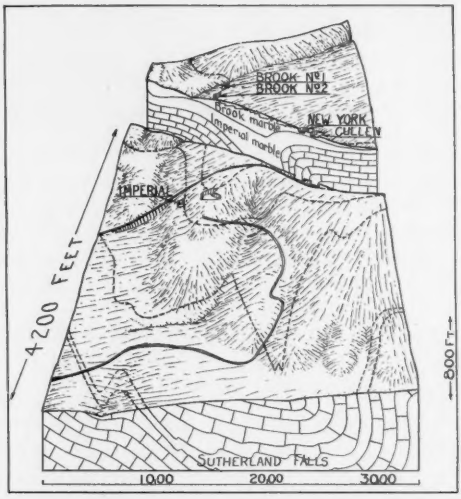


FIG. 6. Block diagram showing structure of Danby deposit; looking south along the syncline. A dolomite bed forms the roof of the Brook marble deposit. The folds in this bed are overturned towards the center of the major syncline from Brook quarry No. 2 on the east and from the New York quarry on the west. This bed maintains constant thickness (competent bed) but distance between the two ends is shortened by duplication. Shortening in the marble takes place by thickening of individual beds with accompanying increase in size of crystals. All workable deposits of calcite marble in Vermont have this structure.

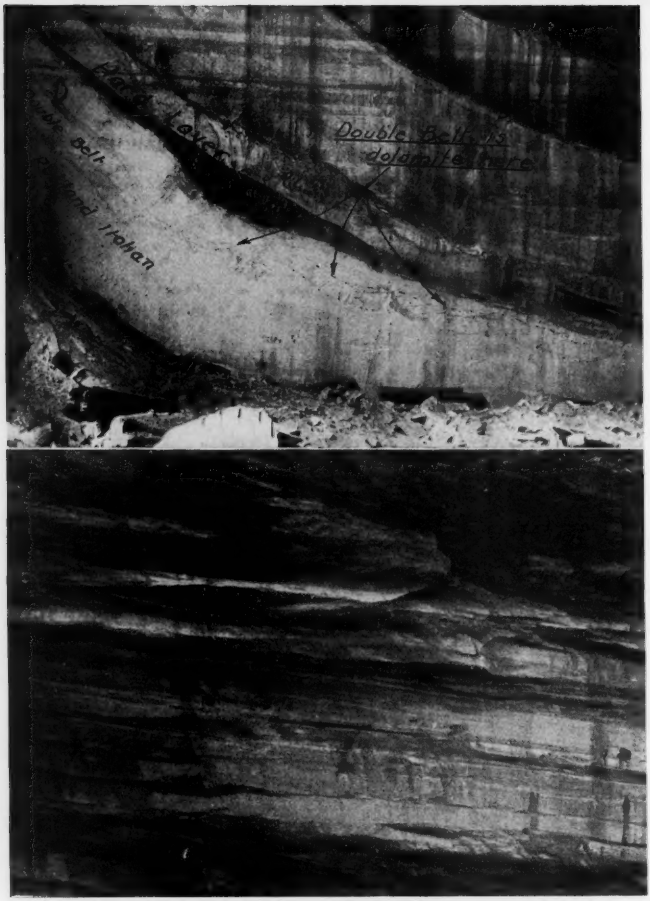
the " A " bed as the quarries attained depth and was designated the " XA " marble. The XA, G′, H, J, M, Q, and V beds contain abundant green silicates; the L bed is almost white and the others are some shade of blue or gray. Some quarries on this

deposit reach a depth of 300 to 400 feet and are numbered from south to north 3, 6, 4, 1, 5, 2, 7 and 8 prospect; numbering follows their order of development. The G′ bed has white marble on either side of a wide green silicated band in all openings except Nos. 7 and 8. All beds east of " M " are concealed at No. 7 quarry; at No. 8 stripping, all beds east of " H " are very thin, the white marble of G′ is blue and the green silicates are nodules of dolomite. Farther north the G′ bed becomes white marble bordering a green silicate band as in the southern openings (Fig. 4).

The same type of change is encountered in the West Rutland deposit. One of the significant openings is the Sherman quarry near the north end of the series, and the most important beds for this study are those near the bottom of the Main deposit; beginning with the oldest at the bottom they are as follows:

Hard layer
Double Belt
Rutland Italian
Bottom Blue Marble (Maclurites bed)
Bottom Blue Lime (dolomite bed).
West Blue Marble deposit.

The Hard Layer, the Double Belt and a green stripe in the Rutland Italian show the same succession of changes but the Double Belt is used in the following description because it is easiest to illustrate and identify. The Double Belt is so named because it is a clear white marble between two regular, green silicate belts, each about one fifth the width of the intervening white (Fig. 7). The Sherman quarry operators removed nearly vertical beds of stone from the surface (elevation 519 feet) down to an elevation of 320 feet by a series of horizontal floors; at this level the deposit flattened out to an eastward inclination and they followed it by tunnels and inclined floors. The Double Belt silicate bands became dolomite on the north side of the quarry at the 280 foot contour, and the light marble turned gray (Fig. 7). The same change appeared in the Rutland Italian stripe at the 300-foot contour and in the Hard Layer at 225 feet.



FIGS. 7 AND 8.

FIG. 7 (above). North wall of Sherman quarry showing dolomite bed changing to silicate beds of the Double Belt marble where it enters a sharp fold and the deposit begins to thicken. Horizontal lines on wall are water marks. Smoothly curving lines are parallel to the bedding.

FIG. 8 (below). East side and roof of Main quarry, West Rutland, showing relations of the white and gray marble in the same bed. The roof white beds have numerous green silicate bands at the right. The marble is gray at the left or north end. The fingers of white in the central part follow the green silicate bands and disappear where the silicates remain as clay or dolomite bands.

A series of flowage folds strike diagonally southeastward across the quarry floor and the strike of the boundary of change in the marble and silicate bands conforms approximately to the axes of these folds. Diamond drill cores for 300 feet eastward down the dip of the deposit show this diminished degree of metamorphism of the dolomite and blue marble to continue to this greater depth.

A thick bed of green silicates and calcite forms the roof of the Imperial Tunnel at Danby; it becomes dolomitic for small sections of the quarry but this is unusual. The deposit was mapped southward along the east face of Dorset Peak and at about one mile south of the Imperial Tunnel the green silicate bed was dolomite and the marble had a light blue color.

Effect of Thermal Activity.—The Chazyan limestones are gray, dark brownish-gray, or black, due to bitumen where they are unmetamorphosed. Even the low degree of metamorphism at Hinesburg has changed the bitumen to graphite and the brownish-gray limestone to blue-gray marble. This primary blue color is the prevailing tone of the stone except in the vicinity of the green silicate bands; all graphite is absent for varying distances on either side of green silicate streaks and many highly fractured dolomite beds, and the stone is white. But white is not the original color. The general associations of white marble are illustrated remarkably well by the roof marble over the Main Quarry at West Rutland (Fig. 8).

White marble with green markings occurs in the roof at the south end of the Main opening at West Rutland; it interfingers with gray marble at the north end of the quarry and the white fingers border the silicate streaks and their continuation (Fig. 8). The silicates end with the white marble but their general zone continues as thin dolomite lenses or micaceous bedding planes.

Solutions are necessary to replace the carbonic acid of the dolomite in the Sherman and Main quarries by the silicic acid of the Double Belt and other green stripes. Furthermore, silicates such as actinolite and chlorite form in the presence of solutions of moderate to high temperature. Other numerous cases of as-

sociation of bleaching of blue marble with silication at places as widely separated as Pittsford Valley, West Rutland, and Danby indicate the regional importance of the solutions causing these changes and emphasize the rôle of solutions in making marble.

Decolorization of the blue marble along all silicated bands indicates removal of graphite in the solutions. Oblique dark veining in some blue marbles indicates that these solutions deposited graphite as well as dissolved it. Increase in graphite coloring as well as decolorization is an effect of thermal metamorphism by hot solutions. The change differs from simple contact thermal metamorphism in principle by removal of a substance in solution rather than by volatilization, and in effect by having less sharply defined limits and more extensive distribution. This thermal change is not dependent upon depth but upon the solution paths. Exploration in the Sherman quarry shows decrease in silication and decolorization as the beds are followed eastward to greater depth. Also diamond drill cores that began in white Rutland Italian marble at the bottom of the Main West Rutland quarry, entered almost unmetamorphosed black fossiliferous limestone at about 450 feet greater depth.

Most complete silication of the dolomite beds—silication is rare in the blue marbles—occurs in association with great thickening on the flowage folds. Silication is accompanied by greatest decolorization and increase in grain size although both of these changes are influenced by the distance southward in the marble belt and distance downward in the stratigraphic sequence. Decolorization in the central structural unit of open folding and fractured rock is negligible, and whiteness of the stone in the Columbian and Sutherland Falls deposits is due to original freedom from coloring matter.

INTERPRETATION OF OBSERVATIONS.

I offer no summary of features relating to the origin of the white calcite marbles, but present one picture—and the only one known to me which contains all observations in this marble district. This picture has been pieced together out of the great

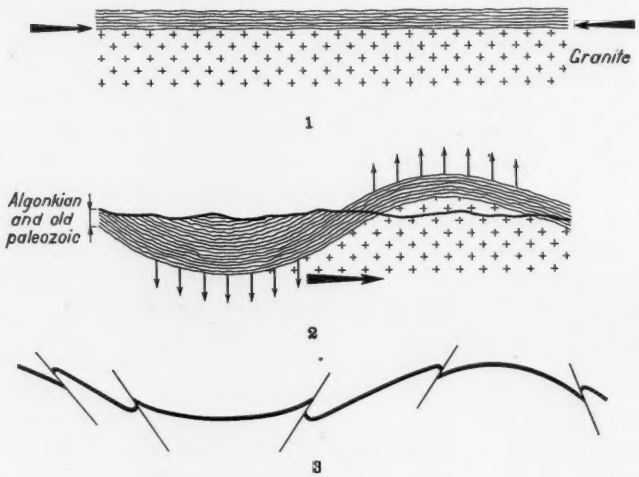
mass of fragmental data gathered in developing and exploring the marble deposits. Relatively pure limestones with occasional dolomite beds became buried, throughout the southern structural unit, beneath clastic sediments of noncalcareous type to such depth that the limestone members were plastic under stress. This semi-plastic deposit flowed slightly towards the center of deepening basins in competent Rutland dolomite. The basins were outlined by the principal geanticlinal movement making the Green Mountains and the domal movements within the bordering geosyncline. These flowage movements cracked the competent dolomite beds interstratified with the incompetent marble. The resultant openings in the dolomite formed the best possible solution channels and most intense recrystallization, decolorization, and silication occurred in the vicinity of these channelways. But these channelways developed in great number over extensive areas only where the great flowage folds formed. Likewise thickening of marble beds to yield blocks of homogeneous marble of commercial size occurs only on the large flowage folds. Flowage folds of suitably large size developed only in the southern structural unit where the cover was great enough to make the marble plastic but not great enough to affect the competency of the underlying Rutland dolomite. This condition is limited in regional distribution to that section of Vermont adjoining the north end and the south end of the Pine Hill-Boardman Hill overthrust.

AMHERST COLLEGE,
AMHERST, MASS.

GENESIS OF THE FISSURE VEINS AT PŘÍBRAM.[1]

BOHUSLAV STOČES.

THE origin of the system of fissure veins in the Příbram district is closely associated with the Variscian folding of the early Palæozoic and Algonkian series of central Bohemia. These sedimentary series were deformed into a succession of anticlines and synclines. The anticlines rest upon cores consisting of enormous intrusions of granite (Figs. 1, 2). The igneous intru-



FIGS. 1–3.

sions apparently took place during the folding as a consequence of the same orogenic movement that produced the folding.

The transfer of magma from beneath synclines to the anticlines is the natural consequence of increasing pressure under

[1] Presented before the Society of Economic Geologists, 13th Annual Meeting, Princeton, N. J., July, 1933.

the down-folding synclines, and diminishing pressure below the rising arches of the anticlines (Fig. 2). The tangential pressure that produced the folding also developed steeply inclined overthrust faults and local folds in the synclines (Fig. 3).

The particular structure to which attention is here directed is that known as the Příbram syncline, which contains the Příbram vein system. This syncline consists of Cambrian conglomerates, sandstones, and shales, with an overthrust of Algonkian shale on one side and a granite contact, four kilometers away, on the other (Fig. 4).

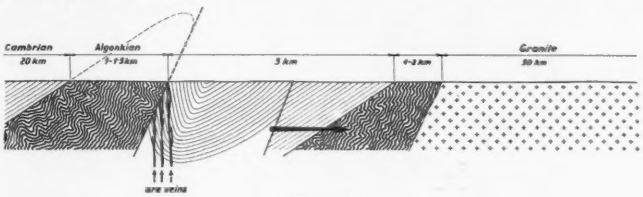


FIG. 4.

In the hard and brittle Cambrian series near the Algonkian overthrust, where the stress was great and the folding most intense, numerous fissures are developed (Fig. 4). The position of the fissures suggests that they follow fractures produced by the overthrust of the Algonkian.

The fissures were filled, first, by diabase, and after the diabase had solidified they were reopened and filled by metalliferous ores and gangue. That the fissures were first filled with diabase and not with granite would indicate that they were not opened until after the upper part of the magma had solidified, at least on the contact. The filling of diabase suggests that the fissures were opened along fractures or planes of weakness after cooling and differentiation of the magma; the diabase being a deep-seated basic segregation, and the fissures the result of the shrinkage of the cooling magma. When cooling and contraction had proceeded sufficiently to open the fissures they were carried down far enough to tap the segregation of diabase.

With continued cooling and contraction of the great granite

batholith, the fissures were re-opened, mostly along the medial planes of the diabase dikes. These planes were evidently of greatest weakness owing to shrinkage of the diabase from the walls inward in the order that freezing progresses (Figs. 5–9).

The interval of time that elapsed between the first and the second opening of the fissures was apparently sufficient to permit

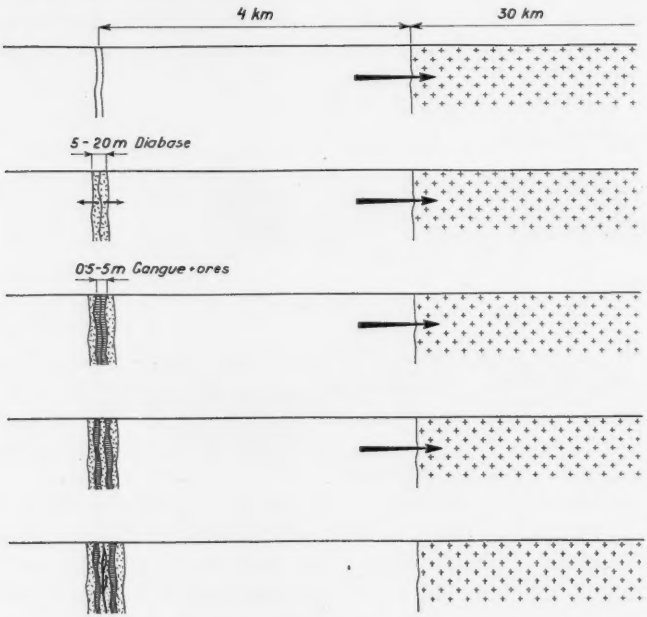


FIG. 5.

the basic segregation to solidify, or possibly the pressure had become too much reduced to lift the magma in the fissures. At all events the new filling of the re-opened fissures consisted of ore and gangue minerals brought up by igneous emanations (Figs. 5–10).

Cooling and shrinking of the granite batholith continued even

after the fissures were completely filled with ore minerals, so that at a later period the fissures were opened a third time and were again filled with a new generation of ores. Repetition of these operations of opening and filling of the fissures continued, evi-

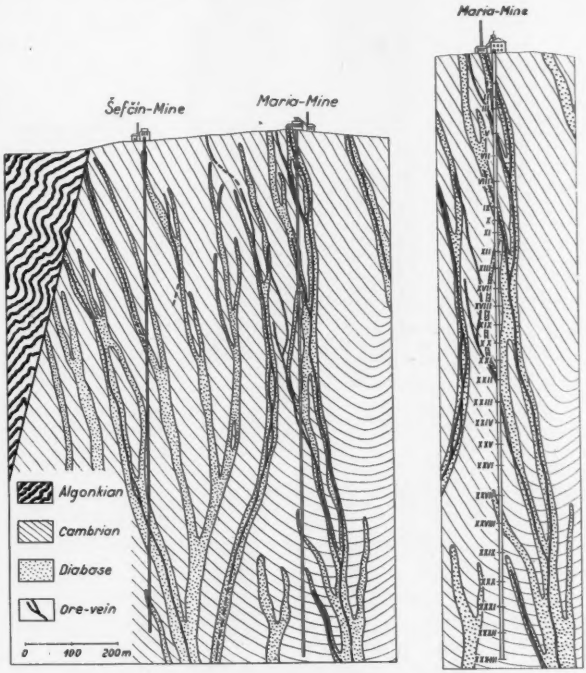
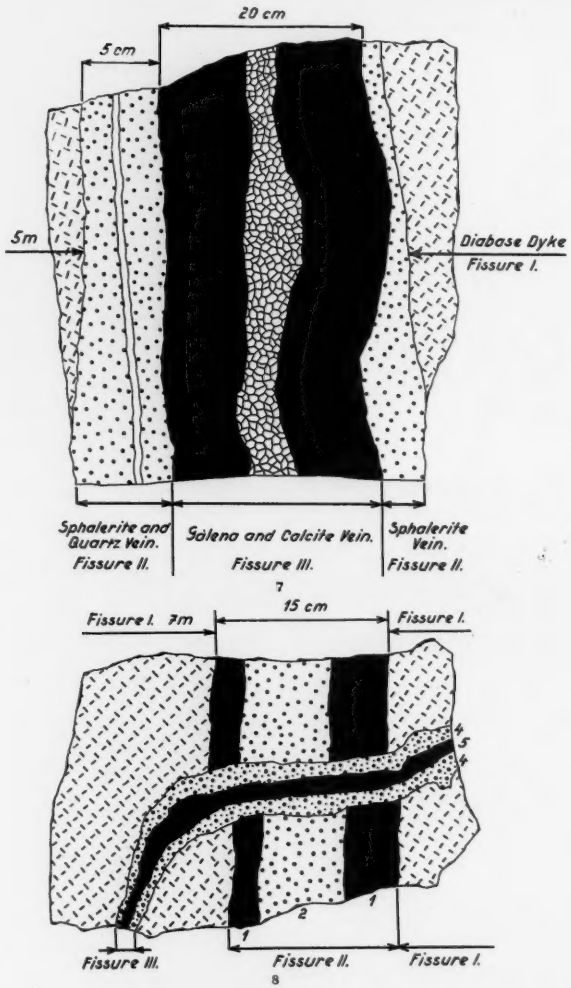


FIG. 6. Section through the Příbram ore vein area. According to Kettner.

FIG. 7. Maria mine. Dotted spaces, diabase; black lines, mineral veins.

dently through a long period, at intervals sufficient to permit changes of composition of successive vein fillings, with the result that no less than 28 generations of minerals were thus deposited. These are, therefore, composite veins of an unusual type, since they are parallel, even occupying the same fissure, yet differing in mineral content (Figs. 6–10).


20 cm
5 cm
5m
Diabase Dyke
Fissure I.
Sphalerite and Quartz Vein.
Fissure II.
Galena and Calcite Vein.
Fissure III.
Sphalerite Vein.
Fissure II.
7
Fissure I. 7m
15 cm
Fissure I.
4
5
4
1
2
1
Fissure III.
Fissure II.
Fissure I.
8

FIGS. 8–9.

The Příbram vein system, therefore, has three interesting characteristics: (1) repeated opening of the fissures by withdrawal of support of the wall rock by slow cooling and contraction of underlying granite magma; (2) opening of diabase dikes,

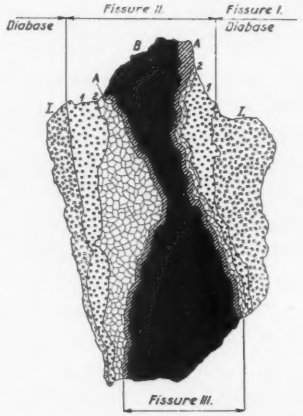


FIG. 10. I, diabase; 1, sphalerite, 2, quartz; A, siderite; B, quartz with sulphides. The first fissure was filled with diabase; by re-opening it was filled with sphalerite and quartz; the third re-opened fissure was filled with siderite and quartz impregnated with sulphides.

the first fissure filling, along medial planes, owing probably to movement of the walls before complete solidification; and (3) composite character of the veins.

NATIONAL SCHOOL OF MINES,
PŘÍBRAM, CZECHOSLOVAKIA.

STRUCTURE FROM SEDIMENTATION AT PARNELL HILL QUICKSILVER MINE, ARKANSAS.

NOEL H. STEARN.

At the Parnell Hill quicksilver mine in the cinnabar district of southwestern Askansas the rocks are standing nearly on end. The backbone of the hill on which the mine is located consists of massive sandstone and quartzite beds that strike about N. 75 E. and dip steeply (72°) to the south.

The cinnabar showings occur in fractures in the quartzite beds that are exposed on the south slope of the hill. From empirical observation it seems that concentrations of cinnabar, like pools of oil, may occur in some vague general relation to anticlines. In order to formulate an exploration campaign it is obviously important to know in which direction to go to find the axis of the anticline. The structural question is simple; *i.e.*, are the beds that contain the cinnabar showings on the south limb of a normal anticline, or on the north limb of an overturned anticline?

Since surface observations of dip have been proven to be wholly unreliable in this region, and fracture cleavage is almost entirely absent even in the incompetent shale partings between quartzite beds, and since the fracture systems in the competent beds, intricately complicated by east-west shortening superimposed on north-south shortening, yield indecipherable or ambiguous conclusions, the structural question is reduced to one of sedimentation; *i.e.*, are the tops of the beds on Parnell Hill facing northward or southward?

A thorough search for the usual criteria for determining the sequence of superposition of beds yields discouraging results. Crossbedding is conspicuously absent. The size of grain is startlingly uniform. In only one place were ripple marks found. These were sub-symmetrical in character. Two competent geologists examined them; one, a member of the U. S. Geological

Survey, the other an economic geologist of over ten years' experience. They arrived at opposite conclusions on the basis of the ripple-mark evidence. There remains only the possibility that a sufficiently careful study of the detailed sedimentary characteristics may unearth a clue which will lead to an unambiguous conclusion regarding the direction of the tops of the beds, from which the geologic structure can be determined.

Figure 1 shows a diagram, drawn to scale, of the stratigraphic section exposed on the west face of a cut driven northward into the south slope of Parnell Hill. The section discloses a series of shales, sandstones, and quartzites, dominantly gray in color, with even, persistent, apparently conformable beds, which range in thickness from an inch to five feet. Except at the south end of the section, which is composed dominantly of shale, the shales are interbedded with the sandstones and quartzites, individual beds of which are almost invariably separated by at least an inch of shale.

Although at the surface, the beds are apparently vertical or dip steeply northward, the dip as disclosed by the trenching is actually 72° south. The change between the dip observed at the surface and that observed in the cut is due, not to regional structure, but to gravity creep and the wedging action of roots, frost, and soil at the erosion surface. An extreme illustration of the effects of this surface action on the attitude of the beds is shown at the south end of the section, where incompetent shale beds with thin sandstone layers have been bent almost 90° from their normal structural attitude. The suggestion of an incipient drag fold appears in the shaly strata about the middle of the section, but it is not sufficiently developed to justify basing structural conclusions on it alone.

A detailed inch-by-inch study of the section reveals that the beds may be grouped into seven zones, according to their megascopically observed characteristics (Fig. 1, A–G).

Zone A is composed dominantly of dark gray to blue-gray, tough clay-shale having a smooth soapy feel. Shale units rarely reach one inch in thickness. The thick layers have faint white streaks parallel to the bedding. It is characteristic of this zone

that the thicker shale units weather into irregular lumps that fracture conchoidally. Although only a few feet of this shale is exposed in the trench, the zone probably extends southward for several tens of feet. Near its north limit are two beds of poorly indurated, fine-grained, white sandstone, about six inches thick, separated by a four-inch layer of dark gray, tough, laminated shale. Each of the sandstone beds contains fragments of dark gray clay-shale concentrated near its south bedding plane.

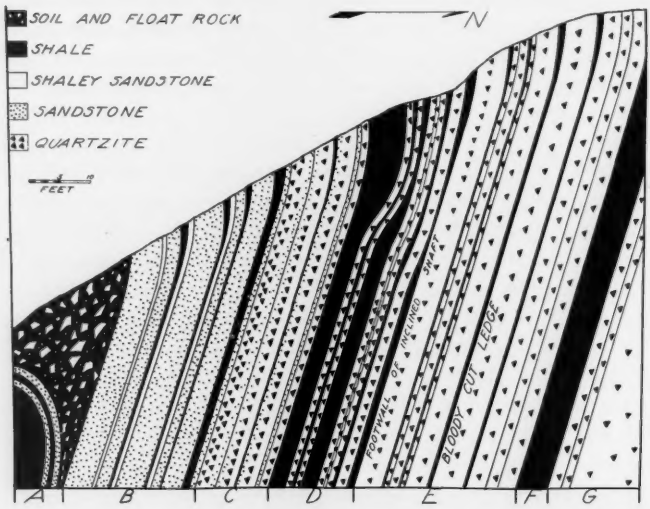


FIG. 1. Detailed stratigraphic section at Parnell Hill cinnabar mine.

Zone B, 20 feet thick, is composed dominantly of massive whitish to yellowish, fine, even-grained sandstone, in beds ranging in thickness from one to four and one-half feet, separated by layers of tough, gray, laminated clay-shale one to two inches thick, or layers of soft, light gray sandy-shale and shaly-sandstone about one-half to one foot thick.

The sharpest planes of demarkation are those between the south faces of the shale layers and the north faces of the sand-

stone layers. A gradation, four times repeated, occurs southward from a massive sandstone bed through a shaly-sandstone bed, a sandy-shale phase of the shale bed, to a finely laminated clay-shale. The sandy-shale phases of the group contain finely comminuted black plant fragments. Near the south edge of the zone a six-inch bed of soft shaly sandstone carries disc-shaped fragments of thinly laminated, gray, clay-shale which reach maximum dimensions of two inches. These are concentrated near the south face of the bed.

The yellowish tinge of the sandstone is caused by iron oxide staining. This takes the form of yellow streaks resembling laminae, mostly less than one tenth of an inch thick, separated by equally thin white streaks. The streaks trace fantastic designs in the sandstone, in some cases resembling cross-bedding, in others intense contemporaneous deformation, and in still others incipient concretionary structures. Careful examination of their space distribution discloses that the yellow streaks are related to avenues of access to solutions; *i.e.*, bedding planes, fractures, and slight variations in porosity.

Zone C consists of eleven feet of sandstone-quartzite in beds ranging from one-half to three feet thick, separated by shale partings up to two inches thick. In fractures in the shale partings brown iron oxide and white dickite are noticeable, with rare "shines" of cinnabar. Fine black plant fragments occur in the shales.

The sandstone and quartzite are not in separate beds but occur as variations in induration of the same bed. Commonly the sandstone phase is the south part of the bed and it is characterized by the fantastically shaped yellow streaks previously noted. The quartzite phase is light gray in color. The south face of the massive quartzite bed in the north half of the group contains rare flakes of black laminated shale, which differ from the gray sandy-shale that occurs immediately in contact with it.

Zone D consists of thirteen and one half feet of interbedded shale and quartzite in beds ranging from one half to two feet thick. The beds of dense, fine-grained, blue-gray quartzite are

much shattered, and the fractures are filled with iron oxide, dickite and cinnabar. The shale beds vary from light gray, tough clay-shale with a soapy feel, through black, fissile clay-shale, to dark gray sandy-shale, containing black plant fragments and pieces of light gray clay-shale. A gradation, seven times repeated in the shale beds, occurs southward from dark gray sandy-shale, containing clay fragments, into dark, thinly laminated clay-shale, which is sharply defined from the quartzite bed at its south contact. Fossils of *Calamites stanleyensis* occur in both the shale and quartzite beds of this zone, one specimen measuring over a foot in length and two inches in diameter.

Zone E consists of twenty-five feet of massive, light gray quartzite in beds from one-half to five feet thick, separated by shale layers up to six inches thick. The quartzite is fine-grained and evenly indurated. The bedding planes are mostly smooth and free from significant markings. In two places, however, the south faces of quartzite beds show undulations which can be attributed to wave action. The most important of these occur on the south face of an eighth-inch quartzite bed, about the middle of the south half of the group. Here the undulations are symmetrical and nearly vertical. The crests are ten to twelve inches apart and the troughs two to three inches deep. In one place, undulations nearly at right angles to the vertical set, and superimposed upon them, form a set of interference wave marks making a group of pits and reticulated ridges. The pits are about six inches across and three inches deep.

A six-inch bed that forms the south contact with the quartzite, consists of a gradation from sandstone through sandy shale to clay shale. The sandstone shows laminae up to one tenth of an inch thick, which reveal irregular cross-lamination, and some contemporaneous deformation. The cross-lamination is truncated by the south bedding plane. The laminations are conformable with the irregular surface of the quartzite bed to the north, thickening and thinning over that surface. The thickening occurs in the depressions in the south face of the quartzite; the thinning occurs over the protuberances.

Rare sandstone pebbles occur in the thin sandstone layer south of the quartzite. Around these the laminae lap, thinning on the southward side and dipping away from the pebbles towards the northward bedding plane.

In the shaly-sandstone a specimen of *Calamites stanleyensis* was found with the delicate reed flutings on its north side meticulously preserved and its south side smooth.

In three places faint suggestions of vertical fracture cleavage appear in the shale partings between the massive quartzite beds.

A peculiar and distinctive phenomenon appears on the south faces of several of the quartzite bedding planes. This was intensively studied on the foot-wall of "Bloody Cut," an east-west trench that exposes a bedding plane over an area 110 feet long by 20 to 60 feet high. The phenomenon consists of conchoidal

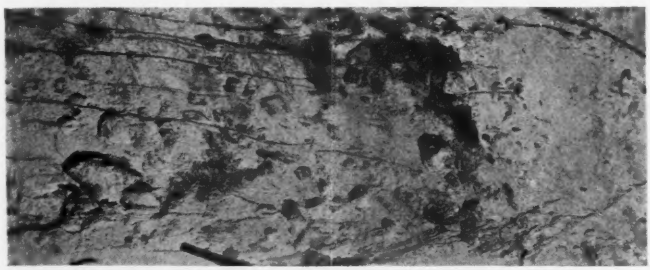


FIG. 2. Photograph of south face of "Bloody Cut" footwall ledge at Parnell Hill mine, showing peculiarly pitted surface of the quartzite.

pits in the south surface of the quartzite beds (Fig. 2). Nowhere were they noted on north bedding planes. They measure from two feet to fractions of an inch across and from three inches to paper thickness in depth, but most of them are about two to four inches across and one half inch deep, the large ones being comparatively rare.

Over 100 of these pits were carefully excavated. Invariably the bottoms are concave, and the pits contain shale, but the character of the shale differs. A fine, gray, thinly-laminated, smooth

clay-shale completely fills some of the pits. This shale resembles the gray shale fragments found in the sandstone beds in zones A, B, and D. Disc-shaped fragments of it also occur completely embedded in the same quartzite. In one place a pit ten inches long, three inches across, and three inches deep contained this type of shale with the laminae curled into a cylindrical shape. In all pits where this shale is found, the laminae are concave southward, conformable with the conchoidal bottoms of the pits.

Others of the pits are completely filled with a dirty gray, unlaminated sandy-shale containing minute black plant fragments.

Many of the pits, however, contain both types of shale. In these cases the laminated clay-shale is always at the bottom, with the fossiliferous sandy-shale above. Sometimes concentrations

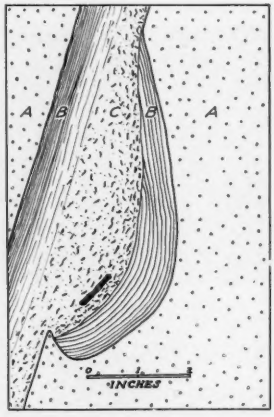


FIG. 3. Diagrammatic section of one of the pits shown in Fig. 2. *A*, quartzite; *B*, clay-shale; *C*, sandy-shale with plant fragments and a *Calamites stanleyensis* fossil.

of plant fragments and even fossils of *Calamites stanleyensis* are found between the clay-shale and the sandy-shale.

Figure 3 shows a diagrammatic cross-section of one of the pits with the two types of shale filling. It is to be especially noted

that at the edges the shale commonly extends under the quartzite, which may form a sort of flange, giving the pits a shape like a mussel shell. It is also to be noted that the shale layer, which is directly contiguous to the pitted surface, consists of gray sandy-shale with black plant fragments, similar to that found in some of the pits.

Zones F and G were projected to the plane of this section from exposures along the strike of the beds. Zone F consists of five feet of shale, sandy at the north face, grading southward through dark gray, fossiliferous, fissile shale to tough, light gray clay-shale with a soapy feel. Zone G consists of massive quartzite beds similar to those in zone E. These beds continue northward for several tens of feet.

CONCLUSIONS.

From this review of certain of the observed facts regarding the stratigraphic section, the inference can be drawn that the sediments were deposited in the neritic zone [1] of deposition. This is suggested by the regularity of bedding, the fineness and evenness of grain, the absence of cross-bedding and ripple marks, the rarity of cross-lamination, the amplitude of the rare wave marks, and the broken character of the fossil plant fragments. The whole sedimentary series may be considered to constitute a transition from sandstone deposition to shale deposition or vice versa. The sum total of the various phases of evidence seems preponderantly to indicate that the transition was from sandstone to shale; *i.e.*, that the tops of the beds are now facing south. The phases of evidence to be reviewed are five-fold:

1. *Wave Marks.*—The undulations on the south face of a quartzite bed in zone E (Fig. 1), with crests ten to twelve inches apart and troughs three inches deep, suggest wave marks. Because the crests protrude from the south face of the bed, they represent the actual ripple structures rather than the counterparts, and indicate that the south face of the bed is its top.

[1] Twenhofel, W. H., and collaborators: Treatise on Sedimentation, page 857. Williams and Wilkins Co., 1932.

2. *Cross-lamination.*—Even if the undulations reviewed above are not wave marks, their relation to the laminations in the bed immediately south of them indicates that the undulating surface of the quartzite was the surface of deposition for the laminated bed. The fact that the laminations conform to this surface and thicken in the depressions is considered proof that the laminated bed overlies the undulating surface. Added to this is the fact that the laminations are truncated by the south bedding plane of the stratum in which they occur.

3. *Fossils.*—In two cases a fossil of *Calamites stanleyensis* was found in sandy shale, with the delicate longitudinal flutings well preserved on the north side and completely missing from the south side. It is considered probable that the preserved flutings were buried in mud, leaving the other side to be worn by wave wash. The smooth side would thus suggest the top of the beds. In each case the smooth side was found toward the south.

4. *Gradations.*—Inconclusive but corroborative evidence is offered by the gradations from north to south from thick sandstone beds through sandy-shale to thin shale layers. This transition was observed fifteen times in the recorded section. It may, therefore, be considered to represent a minor irregular rhythm of deposition, beginning with the thick sandstone bed and ending with the thin shale.

5. *Pitted Surfaces.*—The peculiar pitted surfaces on the south bedding planes of the quartzite beds may represent a type of intraformational conglomerate with shale pebbles in a matrix of sandstone. Considered thus, they offer no indication as to the order of superposition of beds, because source beds from which the shale fragments could be derived occur both north and south of the beds where they are found. The fact that they occur on the south faces of the beds might suggest that they form local basal conglomerates in beds facing northward. However, the number of shale-filled pits in which the outer portion of the pit was filled by a type of shale differing from the inner portion, but identical with the shale layer that occurs immediately south of the pitted surface, suggests that here again the pitted surface was a surface of deposition on which the sandy shale was deposited.

The pits themselves are peculiar sedimentary phenomena, and their origin is a matter of interesting speculation. Their shapes, and the mode of occurrence in them of the clay-shale, suggest strongly that originally clay-shale fragments were deposited in the sandstone. After a period of induration, the surface fragments were wholly or partly eroded, leaving depressions in the sandstone into which plant fragments drifted, to be subsequently covered with sandy mud. This means that the pits may have formed as a result of the erosion of a sort of intraformational conglomerate.

Although a series of intraformational conglomerates at the tops of massive sandstone beds may be unusual, it is possible to visualize a theoretical environment of deposition that could produce them: a shallow epicontinental sea, with offshore neritic deposits grading gradually into wide stretches of shallow littoral deposits subject to mud-cracking and formation of clay galls; a period of equable climatic conditions producing an off-shore bed of sandstone, which reflects quietness of deposition in its evenness of grain and thickness, possibly being built up to the base level of deposition; a storm sweeping the clay galls and mud crack flakes out over the sandstone bed; or a depression of the sea bottom, which raised the base level of deposition, resulting in the same transportation of the near shore deposits; a quiet period during which the sandstone becomes partly indurated and after which its surface is subjected to slight erosion which washes out some of the clay flakes entirely and others in part; a gentle depression of the sea bottom, again raising the base level of deposition to permit the deposition over the pitted sandstone surface of muddy near-shore deposits, with their associated plant remains broken by the transportation and redeposition.

With regard to the theory that the shale fragments in the quartzite originated as clay galls, Dr. W. H. Twenhofel, to whom thanks are due for criticism of this discussion, offers the valid objection that clay galls "do not reach the dimensions required by some of the pits, and clay galls in most instances require a surface above water level across which the mud curls can roll

without becoming wet. It is possible for clay galls to develop without exposure but these are invariably small."

Whether or not the clay-shale fragments associated with the pits originated as clay galls, it seems clear that they were deposited as unit clay or shale fragments when the sandstone was being deposited, and subsequently were partly eroded out to form the pits into which the plant fragments and the sandy shale were washed. And this surface of erosion and deposition is the south face of the quartzite bed, indicating that the tops of the beds face toward the south.

In the light of the conclusions which these five phases of sedimentary evidence permit, it is possible to review what was previously entirely inconclusive structural evidence and find that it adds support to the conclusions based primarily on the sedimentary features. For example, the shape of the incipient drag fold in zone D (Fig. 1) suggests that the south beds have moved upward relative to the north beds. Also, in group E, nearly vertical fracture cleavage is faintly developed in certain shale partings, suggesting that the south beds have moved upward relative to the north beds. Because upper beds move upward relative to lower beds in folding, it follows that the tops of the beds must be facing south.

It is therefore possible to say that from a review of the detailed sedimentary features at the Parnell Hill Mine it can be definitely concluded that the beds are on the south flank of a regional anticline whose axial plane is nearly vertical and located somewhere north of the hill.

Missouri Pacific Bldg.,
St. Louis, Missouri.

THE EVOLUTION OF THE MINERAL COALS.

PART II.

J. VOLNEY LEWIS.

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Conversion of Vegetal Debris into Peat.

"On the surface of the bog we see the growing plants; a little below the surface their recognizable remains; still deeper we find a black semigelatinous substance from which the vegetable fiber has largely disappeared. This substance, saturated with moisture,

is peat."[28] Similar relations are found in forested swamps, which represent more nearly the coal-forming conditions.

Despite active oxidation in the course of vegetal decay in the air, oxygen is rapidly reduced under water by the elimination of the simple oxides, water and carbon dioxide. Hence peat, in all of its variations, is markedly lower in this element and higher in carbon than are the plant materials from which it is derived. Hydrogen escapes in intermediate proportion, as compared with carbon and oxygen, so that its relative abundance in peat remains very nearly the same as in the original forest debris. The striking feature of the analyses, Table I, is the loss of oxygen. Between the falling of the vegetal remains and their submergence and partial preservation in the swamp water, a period of rotting in the open air generally intervenes. For much of the material this stage may continue for many years, during which some of it is completely destroyed. This is the stage of maximum losses. The softer and more perishable tissues yield first. Following these the firm hemicelluloses and most of the cellulose are destroyed. The lignin, on the other hand, degenerates into humus and is largely preserved. The resins and the resistant waxy cuticles remain unchanged.

In both the atmospheric and the subaqueous stages of decay the substances given off are mainly simple binary compounds, of which water, carbon dioxide, and methane are the chief. These two stages may alternate repeatedly, with fluctuations of the water level. To the humic products and woody fragments that accumulate beneath the level of the swamp waters must be added certain fresh materials that become submerged and thus escape the stage of drastic decomposition in the air. These include some of the leaves, the fallen trunks of living trees, and the roots that grow beneath the water level. Much of the submerged material disintegrates into pasty black humus, but remnants of wood in every stage of partial decay still remain.[29] In immature

[28] Clarke, F. W.: Data of Geochemistry. U. S. Geol. Surv. Bull. 770, p. 760.

[29] H. Borntraeger found 25 to 60% of humic substances in black peat and 30 to 60% of vegetable fiber. In the lighter colored varieties the fiber content is higher. (Zeitschr. anal. Chemie, vol. 39, p. 694, 1900; vol. 40, p. 639, 1901.)

FIG.
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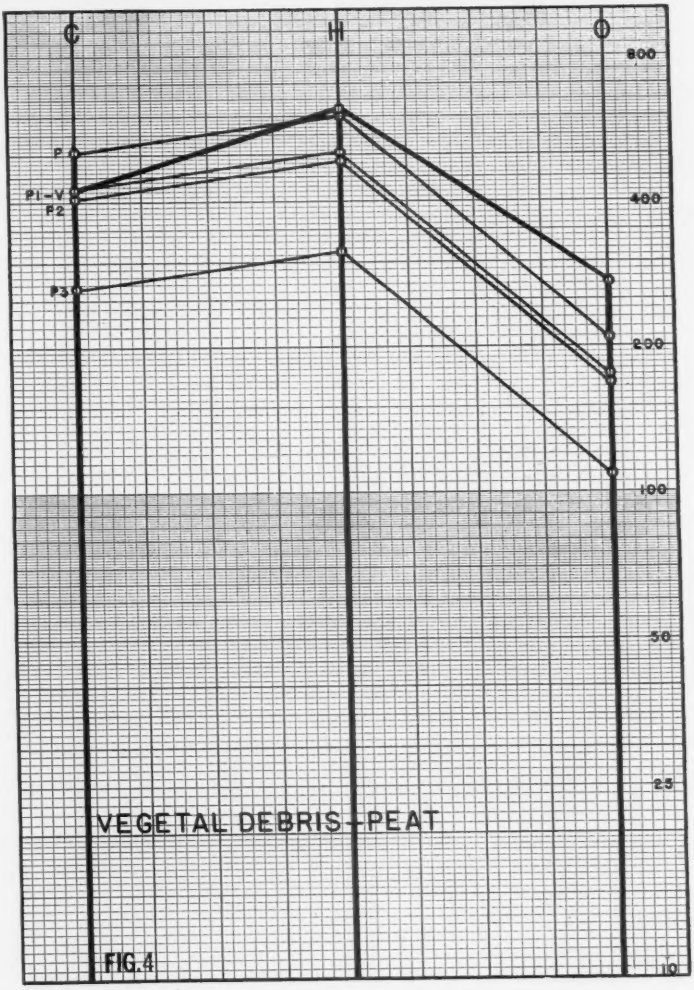


FIG. 4. Diagram on logarithmic scale, showing transformation of vegetal debris (V) into peat (P). Graph V shows the average composition of wood, representing the coal-forming forest debris; P, average peat; P-1–P-3, peat as a residue of wasting vegetal materials, under assumptions (1)–(3).

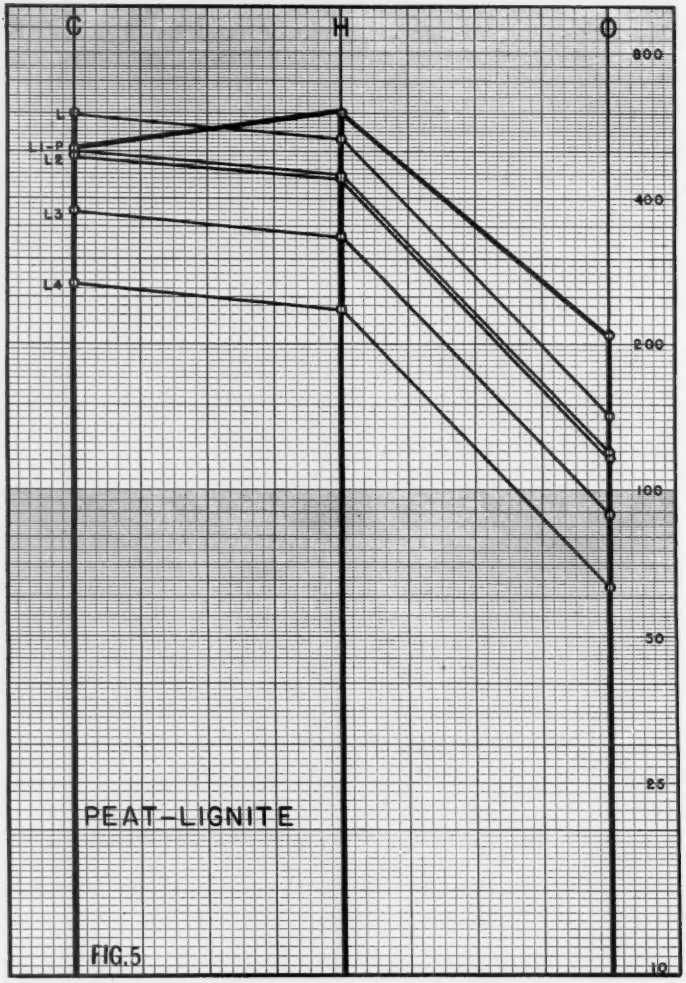


FIG. 5. Diagram on logarithmic scale, showing transformation of peat (P) into lignite (L). Graph P shows average atomic composition of peat; L, of lignite. L-1–L-4 represent lignite as residue of wasting peat after losses under assumptions (1)–(4).

peat such woody fragments constitute the greater part of the mass; and the microscope shows that most of the common coals have been derived from peaty accumulations of this xyloid, or woody, type.

Peat in the swamp or bog may contain as much as 90, or even 95% of water, most of which is held in intimate combination with the humic colloids. This accounts for the fact that little of the water in peat can be squeezed out by mechanical pressure; also, once eliminated by drying, it is largely irreplaceable. That is, the dehydration of the humic complex is an irreversible process. Hence peat that has been dried has lost its cementing power and can not be manufactured successfully into bricks.

Dried peat ranges from light brown to brownish-black in color and generally weighs 40 to 50 pounds per cubic foot (Table II). Extreme examples, however, fall as low as 7 pounds and range up to 65 pounds, depending on the degree of maturity, or extent of humification and compaction. Both of these characters vary with depth below the surface of the swamp or bog and with other factors. For present purposes a median weight of 45 pounds per cubic foot (specific gravity 0.72) is assumed. Also for purposes of comparison, a median weight of 15 pounds of dry matter per cubic foot is assumed for the mat of vegetal debris as it accumulates at the surface of the swamp. Thus average peat has a density about three times as great as the surface materials.

The average losses of materials during the conversion of vegetal debris is estimated at 30%, 70% of the original plant substance remaining as peat (Fig. 14). Estimates of losses at this stage are restricted to such plant materials as contribute some portion of their substance to the accumulating peat. Data are lacking on which to estimate the proportion of the total vegetal growth that suffers complete destruction.

Conversion with Minimum Losses.—(1) With elimination of hydrogen and oxygen only. Using atomic ratios from Table I, Fig. 4 represents the following values:

Graph *V*, Vegetal debris, $C_{421}H_{620}O_{271}$
Graph *P*, Peat, $C_{504}H_{600}O_{209}$

When Graph P is slipped down to the position P-1, where its carbon value (504) coincides with that of Graph V (421), the "spread" between the two curves then measures the loss of 118 hydrogen and 96 oxygen, which is equivalent to 16.5% of the original plant materials, by weight. These elements might unite to form 59 molecules of water, leaving 37 atoms [29a] of oxygen in excess. The residue of 83.5% is thus converted into peat. The foregoing operation may be represented as follows:

Vegetal debris (V)..	C_{421}	H_{620}	O_{271}		
Peat (Graph P-1) ..	421	502	175		
Losses		118	96		
		118	59	H_2O	10.6%
			37	Excess O	5.9%
					16.5%
Remaining as peat					83.5% 100.0%

By calculation the same results are obtained by simple proportion, thus:

$$504 : 421 = 600 : x = 209 : y$$

Whence, $x = 502$; $y = 175$; as above.

FIGS. 6–9. Diagrams on logarithmic scale showing by atomic ratios the conversion of:

6. Lignite (L) into subbituminous coal (SB). In SB-1–SB-4, subbituminous coal is represented as residual from lignite, after losses under assumptions (1)–(4).

7. Subbituminous coal (SB) into bituminous coal (B). Graphs B-1–B-4 represent bituminous coal as derived from subbituminous coal under assumed conditions (1)–(4).

8. Bituminous coal (B) into superbituminous coal (SP). SP-1–SP-4 show superbituminous coal as derived from bituminous, under assumed conditions (1)–(4).

9. Superbituminous coal (SP) into subanthracite (SA). SA-1–SA-4 represent subanthracite as derived from superbituminous coal under the assumptions (1)–(4).

[29a] It is convenient to refer to these atomic and molecular ratios as though they represented the actual numbers of atoms and molecules concerned.

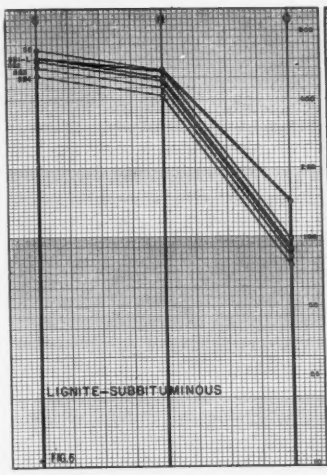


FIG. 6

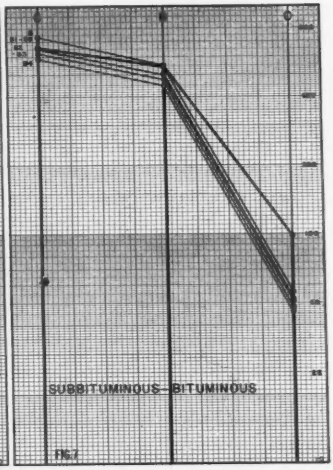


FIG. 7

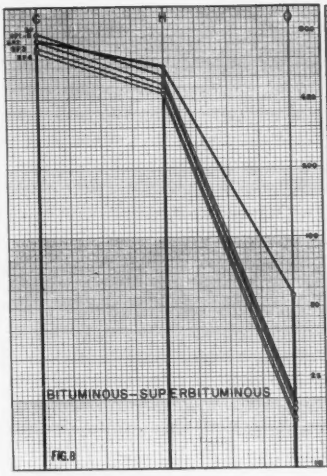


FIG. 8

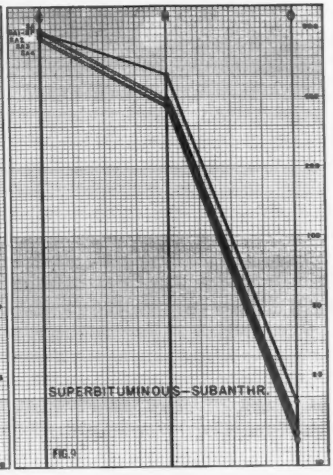


FIG. 9

(2) Minimum losses with evolution of water and carbon dioxide. In seeking the losses of these oxides required to convert the residue into peat, the position of Graph *P*-2, Fig. 4, was found at the scale values indicated below; whence,

Vegetal debris (*V*) ..	$C_{421}H_{620}O_{271}$				
Peat (Graph *P*-2) ..	404	482	168		
Losses	17	138	103		
		238	69	H_2O	12.4%
	17		34	CO_2	7.5%
					19.9%
Remaining as peat					80.1% 100.0%

By calculation the same results are obtained, as follows:

$$C_{421}H_{620}O_{271} - xH_2O - yCO_2 = zC_{504}H_{600}O_{209}$$

(Veg. debris) (Water) (carbon dioxide) (Peat)

Whence are derived the following simultaneous equations:

For carbon, $y + 504z = 421$
For hydrogen, $2x + 600z = 620$
For oxygen, $x + 2y + 209z = 271$

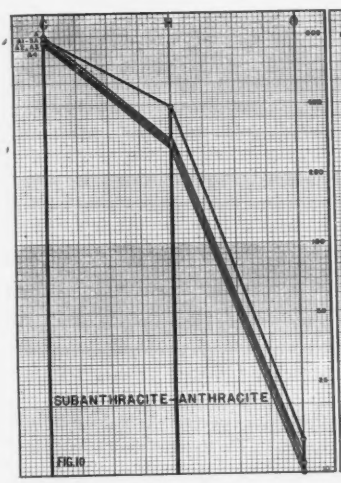
FIGS. 10–13. Diagrams, on logarithmic scale, showing by atomic ratios the conversion of:

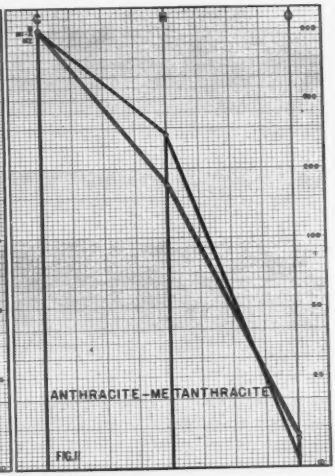
10. Subanthracite coal (*SA*) into anthracite (*A*). *A*-1–*A*-4 represent anthracite as derived from subanthracite coal under the assumptions (1)–(4).

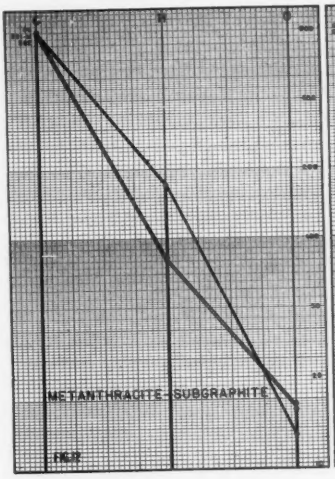
11. Anthracite coal (*A*) into metanthracite (*M*). Graphs *M*-1 and *M*-2 show metanthracite as derived from anthracite under assumed conditions (1) and (2). In this case (3) and (4) introduce no further variations.

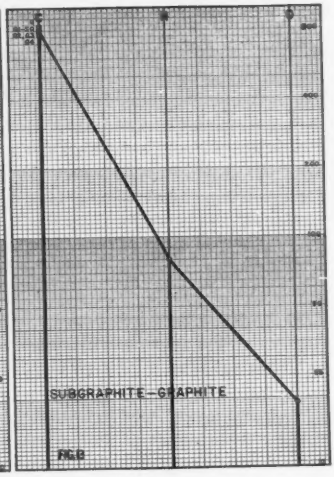
12. Metanthracite coal (*M*) into subgraphite (*SG*). Graphs *SG*-1 and *SG*-2 show subgraphite as derived from metanthracite under assumptions (1) and (2). Again assumptions (3) and (4) introduce no further variations.

13. Subgraphite (*SG*) into graphite (*G*), the final residual carbon. Points *G*-1–*G*-4 show the amount of graphitic residue from subgraphite under the assumptions (1)–(4).


SUBANTHRACITE-ANTHRACITE
FIG.10


ANTHRACITE-METANTHRACITE
FIG.11


METANTHRACITE-SUBGRAPHITE
FIG.9


SUBGRAPHITE-GRAPHITE
FIG.8

Whence, solving, the following values are obtained:

$$x = 69;\ y = 17;\ z = .801$$

That is, the losses under this assumption would be 69 H_2O and 17 CO_2; and 80.1% of the original material remains as peat.

Under the assumption that the elements disengaged shall be in combination as water and carbon dioxide, these losses can not be further reduced. Any higher position of Graph *P*-2, Fig. 4, yields an excess of oxygen (or deficiency of carbon). The minimum losses are set, therefore, by the amount of carbon required to combine with the residual oxygen after providing for the maximum amount of water from the elements eliminated. Any production of carbon monoxide, instead of the dioxide, would increase the losses.

Conversion with Maximum Losses.—(3) Yielding methane and carbon dioxide. Assuming no water to be produced and that both hydrogen and oxygen take away carbon, the losses are thus increased and the peat curve drops sharply to Graph *P*-3, Fig. 4, with the following results:

Vegetal debris (*V*)	$C_{421}H_{620}O_{271}$				
Peat (Graph *P*-3) ..	264	316	109		
Losses	157	304	162		
	76	304		CH_4	12.2%
	81		162	CO_2	35.6%
					47.8%
Remaining as peat					52.2% 100.0%

Or, by calculation, as follows:

$C_{421}H_{620}O_{271}$ —	xCH_4 —	yCO_2	=	$zC_{504}H_{600}O_{209}$
(Veg. debris)	(Methane)	(Carbon dioxide)		(Peat)

Whence are derived three simultaneous equations, as under (2) above, and from these are obtained the following values:

$$x = 76;\ y = 81;\ z = .523$$

That is, the losses are 76 CH_4, 81 CO_2, equivalent to 47.8% of the original materials, 52.2% being converted into peat. Any lower position of Graph *P*-3 yields an excess of carbon, which can not be eliminated in the free state; hence the losses indicated represent the maximum possible with the elimination of methane and carbon dioxide.

(4) Discharging methane and carbon monoxide. Experiments show that the peat curve, under these conditions, drops below the bottom of Fig. 4; hence there can be no Graph *P*-4. The following distribution of the elements in the plant debris shows that complete decomposition would not produce the theoretical maximum of methane and carbon monoxide, on the basis of the hydrogen and oxygen present. The carbon is slightly deficient. By allotting the elements in different order, an excess of hydrogen or oxygen appears instead. Thus:

Vegetal debris (*V*)..$C_{421}H_{620}O_{271}$

155	620	CH_4	24.8%	
271	271	CO	75.8%	100.6%

—5 (C deficiency)

Or,

$C_{421}H_{620}O_{271}$			$C_{421}H_{620}O_{271}$		
271	271	CO	155	620	CH_4
150	600	CH_4	266	266	CO
20		Excess H	5		Excess O

By calculation, as follows:

$C_{421}H_{620}O_{271}$	—	xCH_4	—	yCO	$= zC_{504}H_{600}O_{209}$
(Veg. debris)		(Methane)		(Carbon monoxide)	(Peat)

Whence, solving,

$$x = 160;\ y = 278;\ z = -.0345$$

Both the excessive losses ($x + y = 103.5\%$) and the deficiency on the peat side of the equation ($z = -3.45\%$) indicate the complete destruction of the forest debris, under the assumption

that maximum carbon monoxide be produced, leaving no residue in the form of peat. In the following stages of peat and the coals the oxygen content has been reduced, so that this situation does not arise again; and beyond the lignite stage the losses with the evolution of carbon monoxide are but little in excess of those with carbon dioxide.

In order that the calculations on the basis of this maximum theoretical loss may be carried through the later stages, it is assumed that the destructive process is only half completed in the vegetal debris, thus leaving 50% residue as peat. This assumed value is the basis of Graph 4, at the bottom of Fig. 14. Thus starting from peat practically on a par with (3) above, it affords a close comparison in this figure and in Table III. It is necessary to recall, however, that only small proportions of carbon monoxide are actually found in the coal gases, and for this reason little weight is attached to this theoretical maximum; although, for comparison and for the sake of completeness, the calculations are carried through to the end of the coal series.

Conversion of Peat into Lignite, or Browncoal.

Under the influence of its accumulating weight, and eventually under the load of overlying sediment, peat becomes compacted, thus pressing out much of the water that is held loosely in the pores and interstices of the fibrous and woody fragments. Also, the water that is held more tenaciously in the colloids of the humic complex is thus slowly reduced. Altogether, the water content is diminished from the common range of 80 to 90% in the peat swamps to that of 30 to 55% in the compacted lignite, or browncoal, of average weight about 75 pounds per cubic foot (specific gravity 1.20) (Table II). This marks a further increase of 65% over the density of peat and is five times the density of the original vegetal materials.

In similar manner peat, when dried under pressure, becomes hard like coal. The German browncoals, under light sedimentary cover, have remained porous and spongy, much like peat; the American "black lignites," of the same age, under heavy over-

burden, have become dense subbituminous coal. In color lignite and the browncoals range from brown to nearly black. The lighter colors blacken on exposure, possibly as a result of oxidation. Joint cracks are few and widely spaced; hence the lignites break chiefly into slabby blocks, parallel to the bedding. They crumble, or "slack," readily on exposure to the weather, absorb oxygen rapidly, and are subject to spontaneous combustion; hence they can not safely be shipped in open cars nor stored in open stock piles.

As compared with peat, the outstanding feature of the analyses of the lignites (Table I) is the continued heavy reduction in the proportion of oxygen. There is also a notable drop in hydrogen, while carbon shows a marked apparent enrichment, having suffered the least loss. The cells and tissues that survive the drastic biochemical stages are preserved in lignite and the coals, with only gradual changes in composition, reduction in mass and volume, and consequent flattening under pressure.

Maximum and Minimum Losses in Conversion.—Proceeding exactly as in the preceding section, the transformation of vegetal debris into peat, the results below are obtained by graphic trial and by calculation under the four conditions assumed. Fig. 5 represents graphically the following values (Table I):

Graph *L*, Lignite, $C_{600}H_{330}O_{142}$
Graph *P*, Peat $C_{504}H_{600}O_{209}$

(1) Discharging hydrogen and oxygen only. (Graph *L*-1)

Losses, 155 hydrogen, 90 oxygen	15.9%	
Remaining as lignite	84.1	100.0%

(2) With separation of water and carbon dioxide. (Graph *L*-2)

Losses, 80 molecules water	14.4%	
6 " carbon dioxide ...	2.6	
	17.0	
Remaining as lignite	83.0	100.0%

(3) Removing methane and carbon dioxide. (Graph *L*-3)

Losses: 67 mol. methane	10.7%	
60 " carbon dioxide	26.4	
	37.1	
Remaining as lignite	62.9	100.0%

(4) Eliminating methane and carbon monoxide. (Graph *L*-4)

Losses: 91 mol. methane	14.6%	
146 " carbon monoxide	40.9	
	55.5	
Remaining as lignite	44.5	100.0%

Conversion of Lignite into Subbituminous Coal.

The subbituminous coals, or "black lignites," range in color from dark brown to glossy black, which is a marked darkening, as compared with the lignites, or browncoals. The brown color gives place to brownish black as the moisture content drops to some 27 to 30%. In appearance the subbituminous are much like the bituminous coals; but they are poorly jointed, and hence break into slabby masses approximately parallel to the bedding. They do not stand exposure well; and, like the lignites, they are generally subject to slacking and spontaneous combustion, except in the highest grades, in which the moisture content drops as low as 12 or 14%. Continued compaction has increased the density and greatly reduced the moisture content, the range in the subbituminous coals being commonly 12 to 30% (Table II).

The outstanding change in bulk composition, as in the preceding stage, is a further sharp decline in the oxygen content and a marked relative enrichment in carbon. Hydrogen remains proportionally the same as in lignite (Table I).

Maximum and Minimum Losses in Conversion.—Fig. 6 represents graphically the following values (Table I):

Graph *SB*, Subbituminous Coal, $C_{658}H_{540}O_{98}$
Graph *L*, Lignite, $C_{600}H_{530}O_{142}$

(1) Giving out hydrogen and oxygen only. (Graph *SB*-1)

Losses: 38 hydrogen, 53 oxygen	8.8%	
Remaining as subbituminous coal	91.2	100.0%

(2) Releasing water and carbon dioxide. (Graph *SB*-2)

Losses: 25 mol. water	4.5%	
15 " carbon dioxide	6.6	
	11.1	
Remaining as subbituminous coal	88.9	100.0%

(3) Discharging methane and carbon dioxide. (Graph *SB*-3)

Losses: 19 mol. methane	3.0%	
30 " carbon dioxide	13.2	
	16.2	
Remaining as subbituminous coal	83.8	100.0%

(4) Evolving methane and carbon monoxide. (Graph *SB*-4)

Losses: 29 mol. methane	4.6%	
67 " carbon monoxide	18.8	
	23.4	
Remaining as subbituminous coal	76.6	100.0%

Conversion of Subbituminous Coal into Bituminous Coal.

A further considerable drop in the moisture content marks the advance to the bituminous rank, in which the coals range chiefly between 3% and 12% moisture (Table II). Doubtless this loss is due mostly to further dehydration of the humic colloids. The change is also accompanied by condensation to an average weight about 81 pounds per cubic foot (sp. gr. 1.3), which is an increase of only 8% over the density of lignite, but 80% above that of peat. It is about 5½ times the density of the original vegetal debris. The bituminous coals stand exposure well, in contrast with the slacking of lignites and subbituminous coals. The color ranges from grayish black to pitchy black. Most

common varieties are thinly laminated, with greatly varied luster, from bright glossy to dull, in the different layers. The joint fractures generally are roughly cubical and well developed.

The bituminous rank includes a great heterogeneous group with widely varied properties—coking and non-coking coals, gas coals, splint coals, bogheads, and the high-hydrogen bituminous cannels. Besides the relative increase in carbon, the striking feature of the analyses of bituminous coals, as compared with those of subbituminous, is again the marked decline in oxygen, while the proportion of hydrogen still continues essentially unchanged (Table I). The rapid reduction of oxygen up to this point in the coal series accords with the observed abundance of carbon dioxide among the exhalations from the coals of the lower ranks, although much of the oxygen is disengaged also in the newly formed water.

Maximum and Minimum Losses in Conversion.—Fig. 7 presents graphically the following values (Table I):

Graph *B*, Bituminous coal, $C_{713}H_{550}O_{56}$
Graph *SB*, Subbituminous coal, $C_{658}H_{540}O_{98}$

(1) Eliminating hydrogen and oxygen only. (Graph *B*-1)

Losses: 33 hydrogen, 46 oxygen	7.7%	
Remaining as bituminous coal	92.3	100.0%

(2) Abstracting water and carbon dioxide. (Graph *B*-2)

Losses: 21 mol. water	3.8%	
13 " carbon dioxide	5.7	
	9.5	
Remaining as bituminous coal	90.5	100.0%

(3) Liberating methane and carbon dioxide. (Graph *B*-3)

Losses: 16 mol. methane	2.5%	
25 " carbon dioxide	11.0	
	13.5	
Remaining as bituminous coal	86.5	100.0%

(4) Producing methane and carbon monoxide. (Graph *B*-4)		
Losses: 23 mol. methane	3.7%	
52 " carbon monoxide	14.5	
	18.2	
Remaining as bituminous coal	81.8	100.0%

Conversion of Bituminous into Superbituminous Coal.

Beyond bituminous coal the elimination of moisture is no longer a prominent factor in the advance to higher rank, since only small and irregular changes are found in the moisture content. A slight further concentration is accompanied by a continued rise in fixed carbon and a drop in the yield of volatile matter in superbituminous (" semibituminous ") coal, as compared with bituminous (Table II). Jointing, or " cleavage " is more highly developed, so that superbituminous coal generally breaks into small prisms. Chemically there is a further marked drop in oxygen content and a distinct beginning of the long sharp decline in hydrogen that characterizes the anthracite range. The maximum calorific values of the coal series are attained by the superbituminous and the high-rank bituminous coals (Fig. 2).

Maximum and Minimum Losses in Conversion.—Fig. 8 presents graphically the following values (Table I):

Graph *SP*, Superbituminous coal, $C_{767}H_{500}O_{19}$
Graph *B*, Bituminous coal, $C_{713}H_{550}O_{56}$

(1) Releasing hydrogen and oxygen only. (Graph *SP*-1)		
Losses: 85 hydrogen, 38 oxygen	6.9%	
Remaining as superbituminous coal	93.1	100.0%

(2) Giving out water and methane. (Graph *SP*-2)		
Losses: 38 mol. water	6.8%	
3 " methane	0.5	
	7.3	
Remaining as superbituminous coal	92.7	100.0%

(3) Evolving methane and carbon dioxide. (Graph *SP*-3)

Losses: 29 mol. methan	4.6%	
20 " carbon dioxide	8.8	
	13.4	
Remaining as superbituminous coal	86.6	100.0%

(4) Discharging methane and carbon monoxide. (Graph *SP*-4)

Losses: 33 mol. methane	5.3%	
40 " carbon monoxide	11.2	
	16.5	
Remaining as superbituminous coal	83.5	100.0%

It is to be noted that here, for the first time in the coal series, the released oxygen in (1) and (2) drops below the requirements for water; hence, with the newly-formed water in (2), methane appears instead of carbon dioxide. This deficiency of oxygen (or dominance of hydrogen) persists through the rest of the series.

Conversion of Superbituminous Coal into Subanthracite.

This transformation is accompanied by a slight increase in density, a little rise in fixed carbon, and a drop in volatile matter. The most pronounced physical change is the recementing of the much-jointed structure of superbituminous coal into the firm, hard, massive subanthracite (Table II). Chemically the pronounced drop in hydrogen is the leading feature of the analyses (Table I), with moderate further decline in oxygen and a relative rise in carbon. On the whole the chemical changes are less pronounced than the physical. Subanthracite is the first stage in the coal series in which advance in rank is accompanied by a decline in calorific value (Fig. 2).

Maximum and Minimum Losses in Conversion.—Fig. 9 represents graphically the following values:

Graph *SA*, Subanthracite coal, $C_{782}H_{290}O_{14}$
Graph *SP*, Superbituminous coal, $C_{767}H_{500}O_{19}$

(1) Losing hydrogen and oxygen only. (Graph *SA*-1)

Losses: 117 hydrogen, 5 oxygen	2.0%	
Remaining as subanthracite	98.0	100.0%

(2) With discharge of water and methane. (Graph *SA*-2)

Losses: 6 mol. water	1.1%	
30 " methane	4.8	
	5.9	
Remaining as subanthracite	94.1	100.0%

(3) Releasing methane and carbon dioxide. (Graph *SA*-3)

Losses: 34 mol. methane	5.5%	
3 " carbon dioxide	1.3	
	6.8	
Remaining as subanthracite	93.2	100.0%

(4) Liberating methane and carbon monoxide. (Graph *SA*-4)

Losses: 35 mol. methane	5.6%	
6 " carbon monoxide	1.7	
	7.3	
Remaining as subanthracite	92.7	100.0%

Conversion of Subanthracite Coal into Anthracite.

Anthracite marks a further increase in density and hardness. The average specific gravity, about 1.5 (93.5 pounds per cubic foot), is 15% higher than that of bituminous coal and double the average density of peat. Compared with the original vegetal debris, the density has been multiplied sixfold. The color has become grayish iron-black and the luster is submetallic. Anthracite is imbedded in strongly folded strata, except where produced by the heat of igneous intrusions, and the accompanying shales and sandstones have become greatly indurated. Little recognizable bedding remains in the coal, and the joint fractures are strongly developed. Apart from these, anthracite generally breaks with conchoidal fracture.

There is a further rise in fixed carbon, and volatile matter has almost disappeared (Table II). A sharp drop in hydrogen is again the principal change shown by the analyses (Table I), with a further slight reduction in oxygen and a relative rise in carbon. Accompanying the loss of volatile matter and hydrogen, the decline in calorific value, first marked in subanthracite, continues in anthracite (Fig. 2).

Maximum and Minimum Losses in Conversion.—Fig. 10 shows graphically the following values:

Graph *A*, Anthracite, $C_{796}H_{280}O_{11}$
Graph *SA*, Subanthracite, $C_{782}H_{390}O_{14}$

(1) Giving out hydrogen and oxygen only. (Graph *A*-1)

Losses: 115 hydrogen, 3 oxygen	1.6%	
Remaining as anthracite	98.4%	100.0%

(2) Eliminating water and methane. (Graph *A*-2)

Losses: 4 mol. water	0.7%	
29 " methane	4.7	
	5.4	
Remaining as anthracite	94.6	100.0%

(3) Releasing methane and carbon dioxide. (Graph *A*-3)

Losses: 31 mol. methane	5.0%	
2 " carbon dioxide	0.9	
	5.9	
Remaining as anthracite	94.1	100.0%

(4) Producing methane and carbon monoxide. (Graph *A*-4)

Losses: 32 mol. methane	5.1%	
4 " carbon monoxide	1.1	
	6.2	
Remaining as anthracite	93.8	100.0%

Conversion of Anthracite into Metanthracite.

The Carboniferous coal measures of Rhode Island [30] and Massachusetts have suffered intense compression, folding, and faulting, and the coals have been advanced beyond the anthracite range —in some areas far beyond. These may be called metanthracites and subgraphites, respectively. The metanthracites (near Portsmouth, Rhode Island, and Mansfield, Massachusetts) average 1.75 specific gravity (109 pounds per cubic foot) (Table II), or 17% above the density of Pennsylvania anthracite. They are also harder, but more brittle and friable than the Pennsylvania anthracite. The color is ash-gray to bluish steel-gray and the luster submetallic.

For some unknown reason these metanthracites show a notable increase in moisture, the content ranging from 12 to 24%, as against 2 to 5% in anthracite; also for the first time in the series there is an increase in the oxygen content (Fig. 11).[31] These constituents reverse the rule of continuous change by subtraction or expulsion of constituents, which otherwise seems to hold without exception. The further sharp drop in hydrogen, together with the noncombustible character of the volatile matter, brings a sharp decline also in calorific value (Fig. 2).

The Rhode Island metanthracite ignites slowly and with difficulty, snapping and exploding violently, unless previously air-dried, and burns with an intense heat that is destructive to stoves, utensils, and furnace linings.

Maximum and Minimum Losses in Conversion.—Fig. 11 shows graphically the following values:

Graph *M*, Metanthracite, $C_{800}H_{170}O_{14}$
Graph *A*, Anthracite, $C_{796}H_{280}O_{11}$

(1) Losing hydrogen and oxygen only. (Graph *M*-1)

Losses: 111 hydrogen (3 oxygen added)	1.1%	
Remaining as metanthracite	98.9	100.0%

[30] Ashley, George H.: U. S. Geol. Surv. Bull. 615, 1915.

[31] George C. McFarlane (ECON. GEOL., vol. 24, p. 1, 1929) accounts for the increase in moisture in the "superanthracites" of the Yampa coal field, Colorado, on the theory that the heat of the intrusives has distilled off the tarry constituents that seal the pores of bituminous and anthracite coals. He estimates that this occurs above 600° C.

(2) Eliminating water and methane. (Graph *M-2*)

Losses: 28 mol. methane (no water; 2.5 oxygen added)	4.5%	
Remaining as metanthracite	95.5	100.0%

(3) Discharging methane and carbon dioxide. (Graph *M-2*)

Losses: Same as above. (No carbon dioxide, since oxygen is added instead.)	4.5%	
Remaining as metanthracite	95.5	100.0%

(4) Releasing methane and carbon monoxide. (Graph *M-2*)

Losses: Same as (2). No carbon monoxide, since oxygen is added instead.)	4.5%	
Remaining as metanthracite	95.5	100.0%

Conversion of Metanthracite into Subgraphite.

Throughout the coal series the temperature of ignition rises steadily with the increasing proportion of carbon in the successive residues and the corresponding reduction in hydrogen and oxygen content. In the subgraphites this temperature is so high as effectually to exclude them from the category of fuels. They all seem to be amorphous, however, and analyses invariably show appreciable amounts of hydrogen and oxygen.[32] "Superanthracites" produced by igneous contact in the Yampa field, Colorado, are found to have similar composition. Such residues belong definitely to the coal series, and it is probably erroneous to call any of them graphite or graphitic.[33]

The subgraphites at Cranston and Fenners Ledge, Rhode Island, have the average specific gravity of 2.0 (125 pounds per cubic foot), which is 16% higher than the density of the metanthracites in the same field. A pronounced flow structure gives evidence of movement under intense compression which produced

[32] Similar conditions are observed in determining the "fixed carbon" in proximate analysis of coals. This carbon, after heating at 950° to 1,000° C., still retains several tenths per cent. of hydrogen and oxygen, up to one per cent. of nitrogen, and approximately one half of the total sulphur that was originally present in the coals.

[33] F. W. Clarke, *Op. cit.*, pp. 772, 773.

many slip-planes with glistening "graphite" coatings. Numerous films and veins of quartz and pyrite, up to two inches thick, have been formed in the coal beds. The accompanying shales have been metamorphosed into slates and the sandstones into quartzites. Again, as in the preceding stage, there is a further "abnormal" absorption of oxygen. On the other hand, the moisture content has dropped to the range of 4 to 10%, in contrast with the rise to 12 to 24% in metanthracite (Table II).

Maximum and Minimum Losses in Conversion.—Fig. 12 shows graphically the following values:

Graph *SG*, Subgraphite, $C_{802}H_{80}O_{19}$
Graph *M*, Metanthracite, $C_{800}H_{170}O_{14}$

(1) Discharging hydrogen and oxygen only. (Graph *SG*-1)		
Losses: 90 hydrogen (5 oxygen added).	0.9%	
Remaining as subgraphite	99.1	100.0%
(2) Disengaging water and methane. (Graph *SG*-2)		
Losses: 24 mol. methane (no water; 4 oxygen added)	3.8%	
Remaining as subgraphite	96.2	100.0%
(3) Giving out methane and carbon dioxide. (Graph *SG*-2)		
Losses: Same as (2) above, no CO_2	3.8%	
Remaining as subgraphite	96.2	100.0%
(4) Releasing methane and carbon monoxide. (Graph *SG*-2)		
Losses: Same as (2) above, no CO	3.8%	
Remaining as subgraphite	96.2	100.0%

Conversion of Subgraphite into Graphite.

Some graphite deposits in the metamorphic sediments doubtless represent the residues of ancient coals. Some of the extreme Rhode Island products have been condensed to the specific gravity of graphite (2.2, or 137 pounds per cubic foot). On the ash and moisture free basis, some of them run as low as 2.0% of

oxygen and below 0.4% of hydrogen. This composition may be represented by the empirical symbol, $C_{68}H_3O$, in which apparently it is necessary to assume the existence of a large proportion of free carbon.

In the conversion of subgraphite into the final carbon residue, the last remnants of hydrogen and oxygen are supposed to be eliminated. Any remaining traces must disappear when the carbon crystallizes into graphite.

Maximum and Minimum Losses in Conversion.—Fig. 13 shows graphically the following values:

Graph *G*, Graphite, $C_{833}H_0O_0$
Graph *SG*, Subgraphite, $C_{802}H_{80}O_{19}$

(1) Eliminating hydrogen and oxygen only. (Graph *G*-1)		
Losses: 80 hydrogen, 19 oxygen	3.8%	
Remaining as graphite	96.2	100.0%
(2) Removing water and methane. (Graph *G*-2)		
Losses: 19 mol. water	3.4%	
11 " methane	1.7	
	5.1	
Remaining as graphite	94.9	100.0%
(3) Releasing methane and carbon dioxide. (Graph *G*-3)		
Losses: 20 mol. methane	3.2%	
10 " carbon dioxide	4.2	
	7.4	
Remaining as graphite	92.6	100.0%
(4) Subtracting methane and carbon monoxide. (Graph *G*-4)		
Losses: 20 mol. methane	3.2%	
19 " carbon monoxide	5.3	
	8.5	
Remaining as graphite	91.5	100.0%

Tabular Summary.

Table III shows the losses incurred and the calculated percentages of the original vegetal debris remaining in the residues, under the four conditions assumed in the graphic determinations and the calculations, as set forth in the foregoing pages.

TABLE III.

LOSSES AND RESIDUES IN STEP-BY-STEP TRANSFORMATION.

	Total Losses.					Residues of Vegetal Debris.				
	Minima.		Average (Cumulative).	Maxima.		Maxima.		Aver. (*A*)	Minima.	
	(1) *	(2)		(3)	(4) *	(1*a*) *	(2*a*)		(3*a*)	(4*a*) *
Vegetal debris to Peat	(16.5)	19.9	30	47.8	(100) (50)†	(83.5)	80.1	70	52.2	(50.0)†
Peat to Lignite	(15.9)	17.0	50	37.1	(55.5)	(70.1)	66.5	50	32.9	(22.2)
Lignite to Subbituminous	(8.8)	11.1	58	16.2	(23.4)	(63.9)	59.1	42	27.6	(17.0)
Subbituminous to Bituminous	(7.7)	9.5	63	13.5	(18.2)	(59.0)	53.5	37	23.9	(13.9)
Bituminous to Superbituminous	(6.9)	7.3	66	13.4	(16.5)	(54.9)	49.5	34	20.7	(11.6)
Superbituminous to Subanthracite	(2.0)	5.9	68	6.8	(7.3)	(53.8)	46.6	32	19.3	(10.8)
Subanthracite to Anthracite	(1.6)	5.4	70	5.9	(6.2)	(52.9)	44.1	30	18.1	(10.1)
Anthracite to Metanthracite	(1.1)	4.5	72	4.5	(4.5)	(52.6)	42.3	28	17.4	(9.7)
Metanthracite to Subgraphite	(0.9)	3.8	73	3.8	(3.8)	(52.1)	41.0	27	16.8	(9.4)
Subgraphite to Graphite	(3.8)	5.1	74	7.4	(8.5)	(50.1)	38.9	26	15.6	(8.6)

* Little weight is attached to results in columns (1) (1*a*) (4) (4*a*).

† One half of vegetal debris is assumed to remain as peat in order to carry through the calculations in columns (4) and (4*a*).

Alternative Method of Calculation.

Conversion to Graphite.—The median members of the coal series given in Tables I and II may be assumed to represent a continuous gradation from vegetal debris to graphite. The calculations that follow have been made on the further assumption that each member of the series, in turn, eliminates all of its hydrogen and oxygen, thus condensing into one stage the results of a protracted series of changes and arriving at once at the final carbon residue. The limits of losses in these transformations have been calculated on the same bases, (1), (2), (3), and (4), as in the progress from rank to rank in the preceding pages; namely,

Minimum losses:

(1) Eliminating hydrogen and oxygen only;

(2) Eliminating water together with carbon dioxide in the first half of the series, with methane in the second half.

Maximum losses:

(3) Eliminating methane and carbon dioxide;

(4) Eliminating methane and carbon monoxide.

Thus the leap from forest debris to graphite, under these various conditions, yields the following results:

(1) Vegetal debris (V)..	$C_{421}H_{620}O_{271}$				
Losses:	620 271			49.5%	
Carbon residue	421			50.5	100.0%
(2) Vegetal debris (V)..	$C_{421}H_{620}O_{271}$				
Losses:	542 271		H_2O	48.7%	
	19.5 78		CH_4	3.1	
				51.8	
Carbon residue ..	401.5			48.2	100.0%
(3) Vegetal debris (V)..	$C_{421}H_{620}O_{271}$				
Losses:	155 620		CH_4	24.8%	
	135.5 271		CO_2	59.6	
				84.4	
Carbon residue ..	130.5			15.6	100.0%
(4) Vegetal debris (V)..	$C_{421}H_{620}O_{271}$				
Losses:	155 620		CH_4	24.8%	
	266 266		CO	74.4	
No carbon residue	(Excess O) 5		O	0.8	100.0%

TABLE IV.

CALCULATION TO FINAL CARBON AT ONE STEP; YIELD IN CARBON RESIDUES; PERCENTAGES OF VEGETAL DEBRIS.

	Carbon Residues Percentage				Percentage of Vegetal Debris			
	(1)	(2) *	(3)	(4)	(1a)	(2a) *	(3a)	(4a)
Vegetal debris (*V*)	50.5	(48.2)	15.6	0.0 (8.7)†	100.0	(100.0)	100.0	100.0
Peat (*P*)	60.5	(55.0)	29.9	17.4	83.5	(87.6)	52.3	0.0 (50.0)†
Lignite (*L*)	72.0	(64.6)	47.6	39.1	70.1	(74.5)	32.9	22.2
Subbituminous (*SB*)	79.0	(68.6)	56.9	51.0	63.9	(70.2)	27.5	17.1
Bituminous (*B*)	85.5	(72.4)	65.7	62.3	59.1	(66.5)	23.8	14.0
Superbituminous (*SP*)	92.0	(78.2)	75.9	74.8	54.8	(61.6)	20.6	11.6
Subanthracite (*SA*)	93.8	(83.0)	81.3	80.5	53.8	(58.0)	19.2	10.8
Anthracite (*A*)	95.5	(87.8)	86.5	85.8	52.9	(54.8)	18.1	10.1
Metanthracite (*M*)	96.0	(91.7)	90.0	89.2	52.5	(52.5)	17.3	9.7
Subgraphite (*SG*)	96.2	(94.9)	92.6	91.6	52.5	(50.8)	16.8	9.5
Graphite (*G*)	100.0	(100.0)	100.0	100.0	50.5	(48.2)	15.6	8.7

* The results in columns (2) and (2*a*) involve serious errors and must be rejected. Otherwise the table verifies results obtained by tracing the transformations from stage to stage. Compare 1*a*, 3*a*, and 4*a* with corresponding columns in Table III.

† One half of substance assumed to remain as peat and corresponding carbon residue in order to carry through calculations in columns (4) and (4*a*).

In Table IV, columns (1), (2), (3), and (4), are listed the results of this hypothetical transition in one step from each member of the coal series, in turn, to the final carbon residue. The calculations for each have been carried out under the four conditions enumerated above and in the manner illustrated by the foregoing example of vegetal debris.

Assuming that the successive stages lie in the direct line of "flow," or transformation, the percentages listed in any one of these columns should all represent the same amount of actual carbon. Thus, in column (3), for example, the yield of residual carbon from the vegetal debris, through the total loss of hydrogen and oxygen as methane and carbon dioxide, is 15.6%. Under the same conditions bituminous coal yields 65.7% of residual carbon. Therefore, since 65.7% of the bituminous coal is equal to 15.6% of the original vegetal debris, then, by simple proportion, 100%, or all of the bituminous coal, represents the conservation of 23.8% of the source materials ($65.7 : 15.6 = 100 : x$; whence, $x = 23.8$). This value stands opposite bituminous coal in column

(3*a*). The corresponding values in the other columns, (1*a*), (2*a*), and (4*a*), show the respective proportions of the original plant materials that remain as bituminous coal under the various assumptions as to the manner of the transformation.

In column (4), Table IV, it will be noted that the elimination of methane and carbon monoxide from the vegetal materials leads to their complete destruction, leaving no residual carbon. This is shown also by the solution in the illustrative example given above. Nevertheless, for purposes of calculation and comparison it is assumed, as in the preceding pages, where the transformations are followed step by step, that this process is arrested in some manner so as to leave 50% of the forest debris as peat. This value is inserted in parentheses opposite peat in column (4*a*), and 8.7%, the corresponding carbon residue, is placed opposite the vegetal debris in column (4). Thus, starting from peat essentially on a par with (3*a*), column (4*a*) affords a close comparison.

Comparing Tables III and IV, it will be observed that the values given in columns (1*a*), (3*a*), and (4*a*) agree within one or two tenths, which is well within the limit of error in slide-rule calculation. Therefore, under conditions (1), (3), and (4), the final results are the same whether followed from rank to rank throughout the series, or taken at one leap from each rank, in turn, to the final carbon residue.

Erroneous Results under Assumption (2).—The foregoing statement does not apply, however, to the conditions under (2), in which the released hydrogen and oxygen unite to form water, the unbalanced excess of hydrogen or oxygen then uniting with carbon to form carbon dioxide or methane. It has been found that, under these conditions, a constant excess of oxygen appears in the first half of the coal series, from vegetal debris to bituminous coal. During these transformations, therefore, water and carbon dioxide are the products discharged. In the second half of the series, however, from bituminous coal to graphite, hydrogen is disengaged in excess of the requirements for water; hence in these stages water and methane are the products released

together. Changes in the proportions of the volatile products are found from rank to rank under all of the conditions assumed; but in no other than (2) does this variation lead to a change in the resultant compounds in any way comparable to this change in mid-series from water and carbon dioxide to water and methane.

In the present calculations, therefore, the constant excess of oxygen in the first half of the series and that of hydrogen in the second half, under number (2), are thus brought together unnaturally. The results show the production of water in larger proportion than is possible in nature, and this reduces the demand for carbon required to combine with the unbalanced residues. Hence the total losses as thus calculated under (2) are too low and the successive residues are too high. Therefore the results listed in columns (2) and (2*a*), Table IV, must be rejected as erroneous. The other parts of Table IV verify in every respect the results obtained under conditions (1), (3), and (4), as followed from rank to rank in the preceding pages, both by trial with the semi-logarithmic graphs (Figs. 4 to 13), and by calculation.

Average Course of Transformation.

The losses incurred and the corresponding residues, under the various conditions assumed in the foregoing pages, are given in Table III and are shown graphically (by percentage weights) in Fig. 14. Graphs (1), (2), (3), and (4) show, respectively, the results obtained under the various assumptions that are designated by these numbers in the foregoing pages.

It will be observed that the curves in Fig. 14 are all much alike, except in the first two stages—vegetal debris to peat, and peat to lignite. As explained on an earlier page, Graphs (2) and (3) probably show very nearly the actual minimum and maximum losses and the corresponding maximum and minimum residues, respectively. The conditions designated under numbers (1) and (4), and the results shown by the corresponding graphs in Figs. 4 to 13, apparently are theoretically possible, but they are observed to only a limited extent in nature. At most they probably have no greater influence than slightly to raise Graph (2), Fig.

14, and to lower Graph (3). Also, on the basis of experience, it seems wholly probable that the chemical degradation of the coal complex takes place generally through the gradual elimination of water (newly formed), carbon dioxide, and methane in various proportions. The corresponding curves would lie between Graphs (2) and (3), Fig. 14. Carbon monoxide, on the one hand, and free hydrogen and oxygen, on the other, when produced at all seem always to appear in small proportions; so that the overstepping of the approximate limits (2) and (3) probably would seldom occur, and the transgression, at farthest, would be very slight.

Graph A, Fig. 14, marks approximately the median losses and residues between Graphs (2) and (3). This may be taken as an approximation to the average course of the transformations under the varied natural conditions. Data concerning the substances eliminated from the coals at the various stages and under the various conditions are neither sufficiently accurate nor sufficiently numerous to admit of closer estimate. In Fig. 17 the losses of the several elements are shown separately, by atomic ratios, in curves corresponding to the several graphs in Fig. 14. It is notable that the heaviest losses of all elements are incurred in the first two stages—vegetal debris to peat, and peat to lignite.

Up to the bituminous range, hydrogen and oxygen are expelled more rapidly than carbon, and this is true of the remaining hydrogen in the higher ranks; hence the progressive "carbonization," or enrichment in carbon in the residual coals of successively higher rank (Fig. 1). Hydrogen escapes more steadily than oxygen throughout the series. The latter element goes so rapidly in the earlier stages that in the higher bituminous and anthracite coals very little oxygen remains. A strange reabsorption of oxygen marks the metanthracite and subgraphite ranges. The flattening of the hydrogen curves from lignite to bituminous coal appears in the analyses as a relative rise in hydrogen. The drop in the hydrogen curves again beyond the bituminous range, with little loss of oxygen (which is nearly exhausted), coincides with the dominance of methane in the later stages (Fig. 15). The

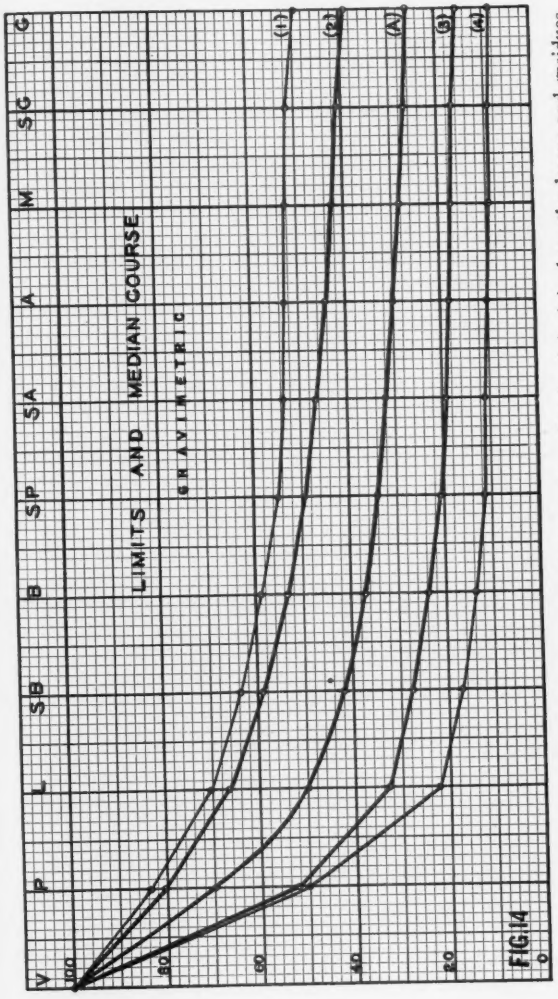


FIG. 14. Graphic summary of transformation results. Graphs (1)–(4) show the losses and residues at successive stages under the assumed conditions bearing the same numbers. Graph (*A*) shows the approximate average, or median, course of transformation. All values are weight percentages. Initials at top represent: *V*, vegetal debris; *P*, peat; *L*, lignite; *SB*, subbituminous coal; *B*, bituminous; *SP*, superbituminous; *SA*, subanthracite; *A*, anthracite; *M*, metanthracite; *SG*, subgraphite; *G*, graphite.

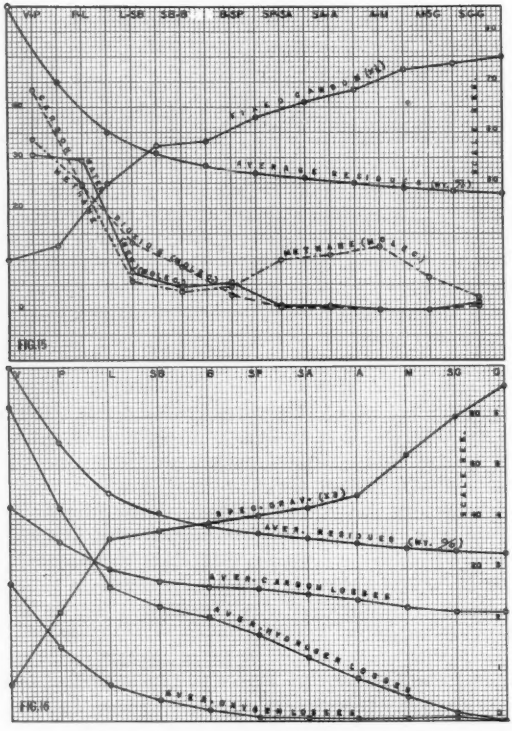


FIG. 15.

FIG. 16.

FIG. 15. Diagram showing average losses of water, carbon dioxide, and methane in the successive transitional stages. For comparison the curve of average residues is reproduced from Fig. 14, and the graph showing the rising median values of "fixed carbon" is introduced. The symbols at the top are: *V–P*, vegetal debris to peat; *P–L*, peat to lignite; etc.

FIG. 16. Diagram showing average losses (atomic) and rising specific gravity with advancing rank. Residues in weight percentages. Initials at top denote the members of the series, as in preceding figures.

average graphitic end-product still retains one half of the original carbon, or one fourth of the total vegetal debris with which the coal series begins. Average anthracite represents 30% of this material, bituminous coal 37%, and lignite 50% (Fig. 14).

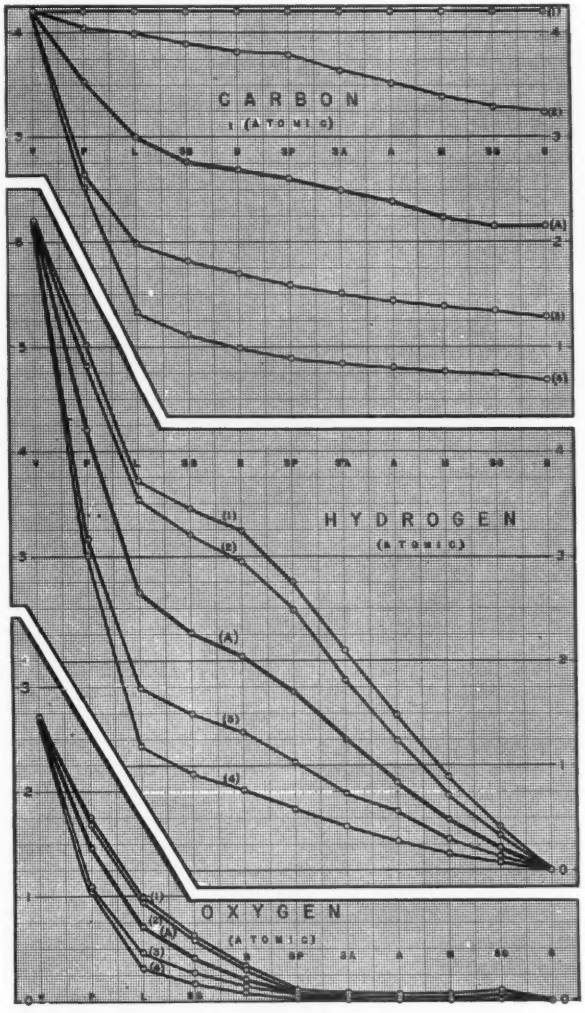


FIG. 17. Graphic representation of the losses by elements under assumptions (1)–(4). Graph (*A*) in each case marks the values that correspond with the average course of transition as shown in Fig. 14, Graph *A*. Atomic proportions. The members of the series are marked by initials, as in the preceding figures.

TABLE V.

CHIEF PRODUCTS ELIMINATED FROM STAGE TO STAGE IN THE AVERAGE COURSE OF TRANSFORMATION.*

	Molecular Ratios.			Weight Percentages.			
	Water.	Carbon Dioxide.	Methane.	Water.	Carbon Dioxide.	Methane.	Total. %
Veg.-Peat	30.6	43.4	33.7	5.4	19.2	5.4	30
Peat-Lignite	29.5	24.4	24.7	5.3	10.7	4.0	20
Lignite-Subbit	7.3	13.2	5.6	1.3	5.8	0.9	8
Subbit.-Bitumin	4.6	8.3	3.5	0.8	3.6	0.6	5
Bit.-Superbit	5.5	2.9	4.6	1.0	1.3	0.7	3
Totals	77.5	92.2	72.1	13.8	40.6	11.6	66
Superbit.-Suban	0.9	0.5	9.9	0.2	0.2	1.6	2
Suban.-Anthracite	0.7	0.4	10.7	0.1	0.2	1.7	2
Anthr.-Metanthr	0.0	0.0	12.4	0.0	0.0	2.0	2
Metan.-Subgraph	0.0	0.0	6.3	0.0	0.0	1.0	1
Subgr.-Graphite	1.5	0.8	2.5	0.3	0.3	0.4	1
Totals	3.1	1.7	41.8	0.6	0.7	6.7	8
Grand totals	80.6	93.9	113.9	14.4	41.3	18.3	74

* Data for this table were derived from the sums of the various products eliminated from stage to stage under the maximum and minimum conditions (2) and (3), as described in the foregoing pages. The sums were then reduced proportionally in each step to the losses in the average course of transformation (Fig. 14, Graph A).

The three principal products of devolatilization—newly-formed water, carbon dioxide, and methane—as eliminated from stage to stage in the average course of transformation (Fig. 14, Graph *A*), are shown in Table V. The molecular proportions are also shown in graphic form in Fig. 15. For comparison the curve of falling residues is reproduced from Fig. 14, and the graph showing the rising content of "fixed carbon" is inserted. It will be observed that most of the eliminated substances are evolved in the first two stages, in which one half of the original material disappears. Up to superbituminous coal, the half-way point of the series (Fig. 3), the losses amount to 66% of the mass. Beyond this, from superbituminous coal to graphite, the total losses amount to only 8%.

A contrast equally striking is presented in the character of the losses in these two divisions. The voluminous products of

the first half contain water, carbon dioxide, and methane in nearly equal molecular proportions—6:7:5.5 (or, by weight, 6:17:5). In the second half the evolution of oxides has nearly ceased. It actually drops to zero in two of the transitions beyond anthracite, where the normal process of change through subtraction is partially reversed while oxygen is being reabsorbed. Here the proportions of the products are 2:1:26 (by weight, 2:2:22). The total losses of the first half are 5 times those of the second half—by weight, 8 times.

In the grand totals the 74% of mass that has wasted away in the long sequence of changes from swamp forest debris to the final graphitic residue, was made up mostly of these three products in the proportions 7:8:10, or, by weight, 7:20:9. Thus the total volume of methane exceeds that of both water and carbon dioxide; by weight carbon dioxide is greatly in excess. Of these two constituents, 63% of the methane and 98% of the carbon dioxide are produced in the first half of the series—51% and 72%, respectively, in the first two stages. Above the rank of lignite, 75% of the remaining methane is given off beyond the superbituminous stage, while 93% of the carbon dioxide escapes before that stage is reached. The newly-formed water goes along with the carbon dioxide; 75% of the total is produced in the first two stages; 85% of the rest is eliminated below the superbituminous rank.

These data reflect the contrasted character of the two great divisions of the coal series, as shown in Fig. 3, Graph *B*. Superbituminous coal stands at a sharp bend in the course. This marks the end of the forward march with the broad front, in which all inherited differences are carried along parallel courses from rank to rank, together with the newly acquired characters.[33b] It stands also at the portal of the long narrow defile, or "bottleneck," into which the coals of every type and shade of difference enter, as they shed their individualities with the rapid depletion of the remaining hydrogen, on which these varied characteristics

[33b] Excellent examples are found in Hickling's "seam curves" of 11 British coal seams. Jour. Inst. Fuel, vol. 5, pp. 318–328, 1932; Colliery Guardian, vol. 144, pp. 401–404, 1932.

depend. Here the broad, undulatory lateral course impinges upon the zero-oxygen line, and the progress that has been shaped largely by the elimination of oxides has come to an abrupt end. The residues are diverted into the narrow path along the oxygen

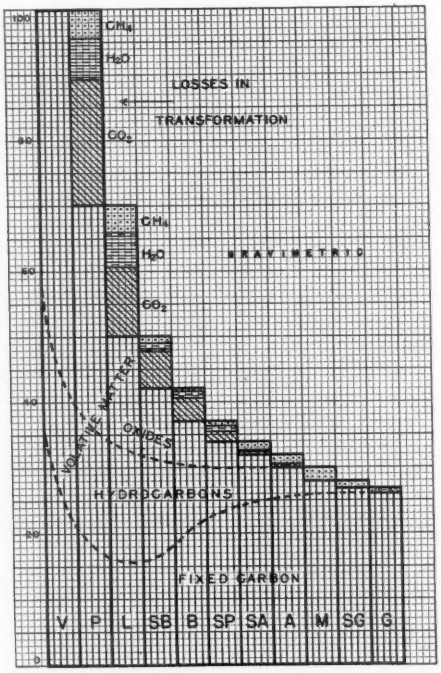


FIG. 18. Diagram showing average losses in transition from rank to rank, also approximate values of fixed carbon and volatile matter in the residual coals. All data are gravimetric. Initials at bottom denote the members of the series, as in preceding figures.

zero, which they follow closely through the anthracites, the metanthracites, and the subgraphites, to the apex of 100% carbon. This final graphitic residue is incapable of further change in character through any process of subtraction or elimination of

constituents. The great, loosely knit molecules of organic matter have finally vanished in air and water, leaving behind but a fraction of one of their elements.

ACCUMULATION AND CONDENSATION.

Rate of Accumulation.—In the present state of knowledge, estimates of the rate of growth and accumulation in the peat-swamps of the coal-forming periods must be highly speculative. Apart from the inadequacy of the data, there were doubtless great variations, in different regions and at different times, in the state of balance between growth and decay. Such estimates in the past have been based largely on scattered data pertaining to peat bogs and swamps in the cool temperate climates of today, although these regions have little in common with the swamps of the Pennsylvanian and other great coal-forming periods, and doubtless their rate of accumulation is much slower.[34] Nevertheless, a brief consideration of this topic from a different point of view may be worth while.

For the mat of accumulating vegetal debris at the surface of the swamp a median dry weight of 15 pounds per cubic foot may be reasonably assumed. This value is well within the range of the springy topmost peat, in which much of the plant material is only partially decomposed. It is about the density of common baled hay and cotton, is one half to three fourths the weight of air-dried cordwood, and one fourth to one half that of solid timber. Furthermore, experience seems to justify the further assumption that the peaty mixture ten feet below the surface will average about 45 pounds of dry matter per cubic foot.

As estimated on a preceding page and as shown in Graph *A*, Fig. 14, 37% of the original forest accumulation may be assumed to remain in average bituminous coal, weighing 81 pounds per cubic foot. It follows, therefore, that 15 cubic feet of the vegetal debris will be required to form one cubic foot of bituminous coal.[35]

[34] White, David: U. S. Bur. Mines, Bull. 38, p. 85, 1913.

[35] As estimated by Otto Kuntze, 400 feet of plant materials, grown in place, would be required to form the coal, 20 to 30 feet thick, in Shansi Province, China; that is, an average of 16 feet of vegetal debris would be required for one foot of coal.

On the same basis a cubic foot of average anthracite would require 21 cubic feet of surface plant materials. Allowing for the gradual compaction in depth and the loss of 30% of the substance during the conversion into peat, these quantities correspond to peat beds 6 feet and 8 feet thick, respectively. For coal seams two feet thick, the peat beds required would be 10 feet and 13 feet, respectively.

Under favorable conditions some forage crops yield annually as much as 10 tons of dry matter per acre, in the limited growing season of the temperate zones. Also it has been estimated that an acre of forest in the temperate zone may produce annually, under human care, 5 tons of dry vegetal substance, of which about 50% is commercial timber, 30% leaves, and 5% roots.[36] The rate of growth in the swamp jungle of southeastern Sumatra is estimated at 8 to 10 times that in the forests of Europe. For the present purpose it seems reasonable to assume that the great coal swamps accumulated annually at least the equivalent of two seasons' growth of sorghum or alfalfa in the United States, or one half the annual jungle growth of the East Indies; say, 20 tons per acre. Thirty-seven per cent. of this became average bituminous coal, one foot of which weighs 1800 tons (of 2000 pounds) per acre; hence it follows that the time required to accumulate the raw materials for this one-foot seam was 240 years.

On the other hand, the maximum rate of accumulation in the coal swamp may have been as great as five times, or possibly ten times, the minimum. At these rates the debris required for one foot of bituminous coal would have accumulated in 48 years or 24 years, respectively. The median values between these rates and the 240 years estimated above at the minimum rate are 132 and 143 years; or, roughly, the accumulations of 125 to 150 years probably have been required for one foot of average bitu-

Furthermore, well preserved plant stems, in changing to bituminous coal, have suffered reduction to one-seventeenth to one-twenty-fourth of their original dimensions, including little or no loss from decay. (David White: U. S. Bur. Mines Bull. 38, p. 89, 1913; Otto Kuntze: Phytogeogenesis, p. 172, 1884.)

[36] Bailey, L. H.: Cyclopedia of American Agriculture, 1907, vol. 2, p. 321.

minous coal and 175 to 200 years for one foot of anthracite. In view of the known luxuriance of vegetation in the great coal-forming swamps and in their diminutive modern representatives, preference should be given, perhaps, to the shorter periods.[37]

Condensation.—As noted, the average density of the surface mat of swamp forest debris is assumed to be 15 pounds of dry matter per cubic foot, and, further, it is estimated that 15 cubic feet of such material is necessary to produce one cubic foot of average bituminous coal. In the average course of transformation, as shown in Graph *A*, Fig. 14, this woody debris has lost 30% of its weight and has become compacted as it passed over into peat, which contained 45 pounds of dry material per cubic foot. Seventy per cent. of the source material was thus converted into 3 cubic feet of peat, which is only 20% of the volume. Corresponding values that have been calculated for the other members of the coal series are listed in Table II, columns (6) and (7).

From these it appears that average bituminous coal, containing 37% of the original forest debris, has been reduced to 7% of the original volume. Compared with peat, the volume is 33%. Anthracite, on the same basis, although retaining 30% of the original materials, has been condensed to 5% of the volume, or 20% of the thickness of the corresponding peat bed.

The close correlation between increasing density and the losses of volatile constituents, particularly that of hydrogen, is shown in Fig. 16. The correlation is less marked with the elimination of moisture and the ratio of volatiles to fixed carbon. These, in general, follow more closely the oxygen curve than that of hydrogen. Thus, despite the heavy losses suffered through devolatilization at every stage of the coal series, it is clear that condensation of the residues has progressed at a far more rapid rate than reduction in mass. G. C. McFarlane[38] has recorded

[37] These figures give a rate of accumulation somewhat higher, and hence require somewhat shorter time, than the earlier estimates. Compare George H. Ashley: Econ. Geol., vol. 2, p. 34, 1907; E. S. Moore: Coal: Occurrences and Properties, p. 146, 1922; David White: U. S. Bur. Mines, Bull. 38, p. 66, 1913.

[38] Econ. Geol., vol. 24, p. 1, 1929.

comparable results among the effects of igneous intrusives in the Yampa coal field, Routt County, Colorado. Comparing the beds at various distances from the intrusive masses, the following densities and relative thicknesses were obtained. For comparison the data in columns (3) and (4) are added from Table II.

	Yampa Coal Field.		From Table II.	
	(1) Specific Gravity.	(2) Relative Thickness.	(3) Specific Gravity.	(4) Relative Thickness.
Regional bituminous coal	1.30	100.0	1.30	100.0
Anthracite	1.42	71.4	1.40	80.0
Anthracite	1.50	66.0	1.50	70.0
Metanthracite ("Superanthracite")	1.71	50.0	1.75	60.0

SUMMARY AND CONCLUSIONS.

A progressive evolutionary series links up the debris of swamp forests with peat, lignite, and the coals. Chemically the transformations are retrogressive, the complex organic substances continually breaking down, with concurrent dehydration and the unequal loss of all constituent elements. The residues show the reduction of oxygen in the earlier stages, the rapid decline of hydrogen in the later stages, and progressive enrichment in carbon throughout the series. (Figs. 1, 2, 14–18). The gradual darkening of color, from light shades of brown to dark brown and black, further characterizes the early stages. Density and hardness steadily increase throughout the series—most rapidly in the development of peat and lignite, and again rapidly in the higher anthracites (Fig. 16).

The changes that underlie these chemical and physical metamorphoses involve: (1) rotting in the open air, with fungal and bacterial activity and rapid, destructive oxidation; (2) subaqueous decay, perhaps largely fermentative, with further losses due to solution; and (3) the long series of subterranean changes, including gravitational compaction, orogenic disturbances, and the rise of interior heat.

Severe losses accompany the first stage, the conversion of

vegetal debris into peat. The processes of dissolution are selective; the softer tissues yield first, the hemicelluloses and most of the cellulose being destroyed, but the greater part of the lignin degenerates into humus and is preserved. The resistant resins and waxes become progressively more concentrated. Tissues and cells that survive this drastic period persist throughout the series, although they steadily lose substance and volume and become flattened under pressure.

Changes in the state of balance between the rate of growth and accumulation, on the one hand, and that of decomposition, on the other, produce layers that differ in the proportions of humins, resins, waxes, and woody fragments. These layers in peat become the thin laminations of the common coals.

Quantitative limits of the losses incurred in transformation have been estimated graphically by trial and confirmed by calculation under four assumptions: (1) with minimum loss of oxygen and hydrogen, all carbon being retained; (2) with minimum evolution of simple compounds, oxygen and hydrogen uniting as water, the excess of oxygen in the earlier stages taking away carbon to form carbon dioxide, the excess of hydrogen in the later stages requiring carbon to form methane; (3) maximum losses, with all eliminated oxygen and hydrogen combining with carbon to form carbon dioxide and methane; (4) like the last. except that carbon monoxide is assumed, instead of the dioxide. Results under these conditions were determined from rank to rank throughout the series (Table III).

The expulsion of free oxygen and hydrogen, as demanded under (1), probably seldom occurs, if at all; also the large proportions of carbon monoxide called for under (4) are not found in nature. Hence the limits set by (2) and (3) are doubtless close approximations to the minimum and maximum losses, respectively, under the varied conditions in nature. Each of these, however, may sometimes be subject to slight modifications. The escape of a little free hydrogen or oxygen may sometimes reduce the losses under (2), while those under (3) will sometimes be increased by the production of carbon monoxide in small amounts, along

with carbon dioxide. Under some conditions also oxidation and solution through the agency of ground water may further increase these losses.

As a check on the results obtained under the foregoing assumptions, alternative calculations have been made on the hypothetical conversion of each member of the coal series, at one step, to the final graphite. Under conditions (1), (3), and (4), the results agree with those obtained in the transformations from stage to stage. Under (2), however, this calculation was found to involve the error of bringing together unnaturally the residual oxygen, which occurs only in the earlier stages, and the excess hydrogen, which belongs wholly to the later stages of the series. Hence the results, as listed in Table IV, columns (2) and (2a), are inaccurate and must be rejected.

The estimated average course of the transformations lies approximately midway between the limits set in (2) and (3) (Fig. 14, Graph *A*) as the changes are traced from rank to rank. It shows one half of the original vegetal debris remaining in average lignite, 37% in bituminous coal, 30% in anthracite, and 26% (one half of the original carbon) left as the final carbon residue, which may become metamorphosed into graphite. Hence average bituminous coal has lost more than 60% of the swamp accumulation. One half of this loss is incurred in the making of peat and one third more in the conversion of this into lignite.

Rough estimates of the rates of accumulation and condensation indicate that 15 cubic feet of the matted forest debris at the surface, or 3 cubic feet of peat, will produce one foot of average bituminous coal. This retains 37% of the original material but has been condensed to 7% of its volume. Average anthracite retains 30% of the forest material in only 5% of the original volume. In comparison with peat, bituminous coal and anthracite retain 53 and 43%, respectively, of the substance, but have been reduced to 33 and 23% of the volume.

It is estimated that the materials required for one foot of bituminous coal accumulated, under average coal swamp conditions, in 125 to 150 years, and for one foot of anthracite in 175

to 200 years. The debris from the swamp forest probably gathered at the average rate of one foot in eight to ten years and average peat at the rate of one foot in 40 to 50 years.

WHITE PLAINS, N. Y.

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DISCUSSION AND COMMUNICATIONS

FERRIC–FERROUS RATIO IN CONTACT–METAMORPHIC DEPOSITS.[1]

Sir: It was with much interest that I read the paper by W. O. Hickok entitled "The Iron Ore Deposits at Cornwall, Pennsylvania," which appeared in the May, 1933, issue of Economic Geology. Mr. Hickok referred therein to my paper[2] dealing with the origin of ferric iron in contact-metamorphic deposits and discussed some of the phenomena at Cornwall in the light of my conclusions as he interpreted them. Part of his interpreta-

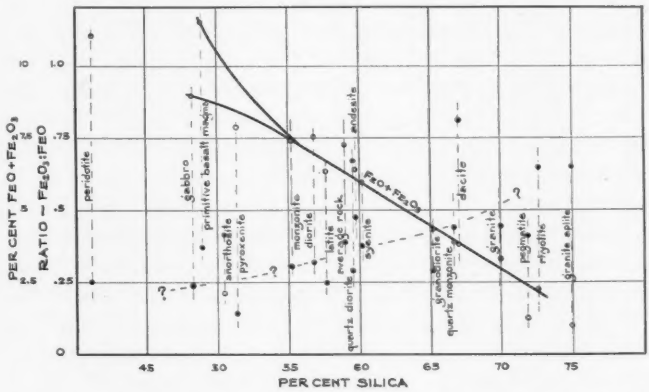

FIG. 1. Diagram showing variation of Fe_2O_3: FeO ratio (dots) in the common igneous rocks as compared with the variation of total iron (circles). Based on Daly's average analyses.

[1] Published by permission of the Director, U. S. Geological Survey.

[2] Lasky, S. G.: The Systems Iron Oxides: CO_2: CO and Iron Oxides: H_2O: H_2, as Applied to Limestone Contact Deposits. ECON. GEOL., vol. 26, pp. 485–495, 1931.

tion is in error, however, and I believe a correction is necessary. Perhaps my meaning was not clear; others also may have misinterpreted my remarks and consequently I would like this opportunity to amplify them somewhat.

Mr. Hickok's summary of my conclusions[3] is as follows, the misstatements being italicized.

> Lasky has modified this (the Butler-Von Eckermann) concept in view of more recent physico-chemical evidence, and shows that Fe_2O_4 will be formed when FeO is oxidized and that a second molecule of CO_2 must react with Fe_3O_4 to produce Fe_2O_3. The second reaction, Lasky says, seldom takes place in nature because of the large preponderance of CO_2 over CO that is necessary to produce hematite from magnetite. Lasky concludes that although the reduction of CO_2 to CO *probably accounts for* the oxidation of FeO to Fe_3O_4, *the presence of Fe_2O_3 must be accounted for by the greater volatility of $FeCl_3$ than of $FeCl_2$, and, therefore, all of the Fe_2O_3 in contact deposits must have been transported in the form $FeCl_3$ and must have been precipitated directly from the chloride as hematite.*

The words "probably accounts for" should read "could account for." The final statement in the quotation is contrary to my true conclusions. I wrote:[4] "(An) explanation considered by many geologists for the high ferric content of contact deposits . . . is that the iron leaves the igneous source in the ferric state as the volatile halides. This may be partly true, but there seem to be insufficient halides present to account for all the ferric iron." Compare this with Mr. Hickok's conclusion concerning the Cornwall deposits; he says:[5] "Without the supposition of a great loss of halogens into the surrounding rocks, there is an insufficient amount of chlorine and fluorine in the minerals at Cornwall to have combined with the iron necessary to form even the small part of the iron ore that was precipitated as hematite." The two statements are nearly identical in thought.

Because oxidation of iron to Fe_2O_3 by carbon dioxide and by water, and transportation of iron as ferric chloride, neither singly nor together seemed to me adequate to account for the great

[3] Pp. 243–244.
[4] *Op. cit.*, p. 493.
[5] P. 244.

quantities of ferric iron in contact deposits, I suggested that "some of the iron may leave the magma *in the ferric state in a form other than the halide.* If mineral-bearing emanations are a product of differentiation there would seem to be no reason why the ferrous-ferric ratio in these emanations should be the same as in the solidified igneous rock which we assume represents their source." [6]

Rock analyses show that the progressive differentiation of magmas is accompanied by a variation in the molecular ferric-ferrous ratio, and a similar variation has been observed in experimental melts.[7] In the primitive basalt magma as calculated by Daly,[8] for instance, the molecular Fe_2O_3: FeO ratio is 1 : 2.7. In the common plutonic rocks it ranges from 1 : 7.4 in the average pyroxenite to 1 : 1.5 in granite aplite; in the effusive series it ranges from 1 : 4 in the average latite to 1 : 1.2 in the average dacite. The accompanying petrographic variation diagram shows the variation of the ferric-ferrous ratio as compared with the variation of the total iron content in the common igneous rocks. There seems to be a tendency for the ratio to increase as differentiation progresses, as shown by the dotted curve, but the possibility of this being a real condition will bear further study and can not be discussed here; the point I wish to make is simply that the ferric-ferrous ratio ranges widely in rock differentiates. If, now, mineral-bearing juices are also magmatic differentiates, a continued change in the ferric-ferrous ratio is to be expected. The ratio is probably high in the deuteric rest-juices that so commonly produce magnetite, and certainly it is high in the solutions that form hypothermal deposits in which specularite and epidote are common. Presumably it is insignificantly small in those that form lower-temperature sulphide deposits. A logical reason for this variation in the ferric-ferrous ratio would seem to be that some of the iron content of magmas and magmatic differentiates exists and migrates in the ferric state and in a

[6] *Op. cit.*, pp. 494–495.

[7] Bowen, N. L., Schairer, J. F., and Posnjak, E.: The System $CaSiO_4$–$FeSiO_4$. Amer. Jour. Sci., vol. 25, pp. 275–297, 1933.

[8] Daly, R. A.: Igneous Rocks and Their Origin, p. 315, 1914.

ratio to the ferrous iron that is controlled by whatever oxidation equilibrium conditions exist at the time.

I do not wish it inferred that I believe all ferric iron in contact deposits was transported as such; on the contrary, it seems certain that all was not so transported. The presence of large quantities of lime silicates in contact zones proves that much carbon dioxide must have been present when ferric iron minerals were deposited. Likewise, moisture must have been present in the invaded rocks, and both carbon dioxide and moisture would have caused oxidation until equilibrium was established. This is only another way of writing my original statement: "Assuming that some of the iron may leave the magma in the ferric state . . . , the task placed upon CO_2 and steam may be lightened to a considerable though unknown degree." [9]

To summarize: The high ferric-ferrous ratio in contact deposits seems to be due to a combination of two independent processes:—(1) Migration, in the ore-depositing differentiate, of part of the iron in the ferric state, but not necessarily nor all together, in the form of ferric chloride; and (2) oxidation of some of the ferrous iron in this differentiate by carbon dioxide and to a lesser extent by steam. Which of the two processes predominates is speculative; perhaps exhaustive quantitative studies may show that enough carbon dioxide and steam were present in certain deposits to have produced a great deal of the ferric iron present, even to the point of being responsible for some of the specularite, whereas in other deposits it may be obvious that they could have produced only a small part.

SAMUEL G. LASKY.

U. S. GEOLOGICAL SURVEY,
SOCORRO, NEW MEXICO.

[9] *Op. cit.*, p. 494.

REVIEWS

Thin-Section Mineralogy. By AUSTIN F. ROGERS AND PAUL F. KERR. Pp. 311, illus. 261. McGraw-Hill Book Co., New York, 1933. Cloth, 6 × 9¼. Price, $3.00.

A welcome addition to the books dealing with the optical characters of minerals and their identification in thin sections is this little volume, which is intended to acquaint the beginning student with comparatively simple methods of identifying the minerals in rocks, without the necessity of spending a large amount of time, beforehand, in "studying the great volume of theoretical information necessary to acquire an advanced knowledge of the optics of crystals." The discussions, though brief, are clear, and are illustrated by a large number of appropriate diagrams, charts and sixty or more halftones from photographs of typical thin sections.

The book is divided into two parts. The first deals with mineral optics and the second with descriptions of the individual minerals that are found in rocks. Orientation diagrams for nearly all the biaxial minerals are inserted in the paragraphs dealing with the minerals to which they refer. The descriptions are very brief, perhaps too brief to be clear in some cases. On the whole they suggest lecture notes, but with a little help from an instructor they should serve their purpose very well.

The first part summarizes such information concerning light and the microscope as is required before the descriptions of the minerals can be understood. The treatment of the subject differs very slightly from that in most text-books, except that while it is very comprehensive and precise it is at the same time divested of all considerations that are not essential to the understanding of the technique required in determinative processes, and is therefore comparatively brief, though sufficient for most purposes. This is due largely to the excellency of the illustrative diagrams, which are exceptionally clear. The concluding chapter in this part of the book describes the procedure for the identification of minerals in thin sections. It is provided with tables based on color, form, cleavage, refractive indices, birefringence, optical sign and magnitudes of axial angles.

The reviewer knows of no book on the optical properties of crystals and minerals more satisfactory than this one for students who are interested in the study of rocks or minerals. It is clear and accurate. It contains enough information for most students of petrography and fur-

nishes a good foundation that can easily be built upon by mineralogists, chemists and physicists who wish to go more deeply into the study of optical crystallography.

W. S. BAYLEY.

Oil and Gas Fields of Michigan. By ROBERT NEWCOMBE. State Geol. Survey of Michigan, Pub. 38. Part of Annual Report for 1932. Price, $2.00 in paper, $2.50 in cloth.

Any petroleum geologist or producer who wishes to obtain comprehensive first-hand information on the rapidly multiplying oil fields of Michigan will find this volume indispensable. For those who must read and run, the author has summarized the contents in the first six pages of the report.

Part I (127 pp.) describes in detail the general geology of the Michigan Basin. All systems of the Paleozoic are represented and each is fully described. Numerous references to the literature indicate that the author has traced down the origin of names and the stratigraphic limits of groups, formations and members. The table of names on pages 22 to 24 includes all the newly established members and other subdivisions now accepted by geologists working in the State. For instance, the Ellsworth formation, which wedges in between the Bedford and the Antrim in the western part of the State, the subdivisions of the Niagaran and of the Medinan as well as the new members of the Ordovician sequence appear in this table.

The isopach maps beginning with the Monroe-Salina (p. 70) reveal many interesting details of geologic history and structure. One is struck by the fact that the deepest part of the basin toward the center of the Southern Peninsula is usually the locus of the thickest accumulations. Also striking is the fact that the salt basins were isolated and that the three periods of evaporite formation have no exact counterparts in adjacent areas (p. 33).

The structural geology is fully described. All the newer theories to account for irregularities in the attitude of strata are examined and considered in explaining the present structural pattern. Differential subsidence, differential compaction, unconformities and convergence are considered, together with basement shearing, horizontal thrust, etc. Interesting anomalies such as the disappearance of the 70 foot closure on the Muskegon anticline below the Salina beds (p. 96) intrigue the geologist who likes puzzles. The author believes that the "uniform, sharp, west dip of nearly all structures in the central part of the State strongly suggests deep-seated faulting as a cause for the location of these structures" (p. 113). Actual subsurface fault phenomena have been found in Livingston County near the city of Howell. The peculiar structural irregularities on the crest of the Muskegon structure are believed to be due to the collapse of the cover following solution of thick salt layers beneath.

Some of the erratic oil production in the Traverse formation is explained by the "local original and secondary porosity of reefs" (p. 120).

In Part II (140 pp.), after a brief summary of the principles of oil and gas accumulation and the oil structures of Michigan, the author treats in detail the Muskegon and the Central Michigan structures. Features common to nearly all anticlines are the small width, asymmetrical cross-section, steep dip toward the basin, sharp cross-folding, arcuate outline, irregular porosity of pay horizons, and thinning or absence of the upper Mississippian rocks on the crest. By contrast the synclines are wide and flat.

The Muskegon pool has four productive horizons, all of which are in the Devonian Traverse and Dundee limestones and the Monroe dolomite. The oil has been found in several domes on an elongated anticline with about 70 feet of closure. The production per acre is somewhat over 2,000 bbls. of oil, and 2½ million cubic ft. of gas.

The Central Michigan Structure includes 8 pools in Midland, Isabella and Clare Counties. These are called Mount Pleasant, East Extension, Leaton, Vernon, Porter, Mecosta, Clare and Broomfield fields. They are located on domes and noses 1½ to 2 miles across, which are superposed on the Greendale and the Broomfield anticlines. Although most of the oil comes from the Dundee and Monroe dolomites, some has also been found in the Marshall (Mississippian) sandstone and in the Devonian Traverse limestone. Gas appears in the Dundee with the oil but has also been found higher in the section in the Mississippian Marshall and Michigan "stray" sands. Curiously enough, the gas seems to occur farther down the flank than the deeper oil. The ultimate recovery is conservatively estimated to be from 4,000 to 5,000 bbls. per acre.

Beginning with Chapter VI, Dr. Newcombe describes the undeveloped structures and also sets forth the results of drilling in counties where no oil has been discovered up to date. The many interesting details of the Howell Structure so far ascertained make one suspect that the best pools yet await discovery.

Although the book went to press before the interesting oil discoveries were made in Ogemaw, Oceana and Montcalm Counties, every geologist will be grateful to Dr. Newcombe for his exhaustive summary of facts pertaining to the oil fields of Michigan.

W. A. Ver Wiebe.

University of Wichita,
Wichita, Kan.

Aufsuchung von Wasser mit Geophysikalischen Methoden. By J. KOENIGSBERGER. Pp. 63, figs. 22. Akad. Verlagsgesellschaft M. B. H., Leipzig, 1933. Price, 3.80 M.

The author, in this booklet, describes the application of geoelectrical methods in the search for water. The discussion is concise but comprehensive. References to sources of fuller information are abundant. It is asserted by the author that by the methods outlined, with the aid of geologic study under favorable auspices and with the occasional help of seismological methods, the boundary limits of a groundwater body may be ascertained, also the quantity of water in storage and its quality. By determining the points of inflow of the supply, the direction of its currents and the dip of the beds through which it flows, the selection of favorable sites for borings is possible.

The book gives an excellent summary of the ways in which electrical methods may be employed in studying groundwater, but the treatment of the subject is too concentrated to be of much value except to one who is engaged primarily in the investigation of water supplies.

W. S. BAYLEY.

The New Background of Science. By SIR JAMES JEANS. Pp. 301. The Macmillan Company, New York, 1933. Price, $2.50.

Like Sir James Jeans' earlier book, "The Mysterious Universe," this book is written for those who have no special knowledge of science and is in part an amplification and clarification of his previous work. He points out that there have been recently two great upheavals in physical science, associated with the words "relativity" and "quanta." He attempts to supply the background to the present new science. His subjects are: The Approach to the External World; Methods of Science; Space and Time; Mechanism; Matter and Radiation; Wave Mechanics; Indeterminacy; Events. His discussions relate to the present philosophy underlying physics, rather than the technical problems of physics. The serious reader in science will find much of interest and profit in them and will be impressed by the author's clarity and his mastery of his subject.

Copies of books mentioned under "Reviews" or under our "New Book List" (see advertisement page) may be purchased through our Journal Bookshop by writing to W. S. Bayley, University of Illinois, Urbana, Ill.

BOOKS RECEIVED.

By

DAVID GALLAGHER.

The Evolution of the Ohio River. By GERARD FOWKE. Pp. 273, figs. 30. Hollenbeck Press, Indianapolis, Ind., 1933. A posthumous volume published by Mr. Fowke's friends in Madison, Wis., dealing with the evolution of the Ohio and its tributaries. An interesting record and discussion of unusual changes and life history of a stream.

Proximate Analysis of Chinese Coals. By K. Y. KING AND T. C. HUNG. Pp. 61. China Geol. Surv. Bull. 21, 1933. (Contribution from the Sin Yuan Fuel Laboratory No. 13.) Tables of coal analyses.

Gemstones. Pp. 137. Imperial Institute, London, 1933. Price, 2/6. Sources, preparation, production and marketing, world occurrence by countries, bibliography.

Some Deposits of Ornamental Stone in Montana. By G. R. MANSFIELD. Pp. 22, pls. 6, figs. 2. U. S. Geol. Surv. Circ. 4. Washington, 1933. Onyx and travertine.

Publications on the Geology, Mineral Resources, and Mineral Industries of Illinois. Pp. 83. Illinois Geol. Survey. Urbana, 1933. Bibliography.

Oil and Gas Possibilities of Parts of Jersey, Green, and Madison Counties (Illinois). By D. M. COLLINGWOOD. Pp. 91, pls. 3, figs. 4, tables 4. Illinois Geol. Surv., Rept. of Inves. No. 30. Urbana, 1933.

The Bleaching Clays. By P. G. NUTTING. Pp. 51, figs. 11, tables 7. U. S. Geol. Surv. Circ. 3. Washington, 1933.

Mineral Deposits near the West Fork of the Chulitna River, Alaska. By C. P. Ross. Pp. 50, pls. 3, figs. 8. U. S. Geol. Surv. Bull. 849–E. Washington, 1933. Price, 15 cts.

Anna Kaolin as a New Decolorizing Agent for Edible Oils. By R. J. PIERSOL, J. E. LAMAR AND W. H. VOSKUIL. Pp. 42, tables 9, figs. 7. Illinois Geol. Surv. Rept. of Inves. No. 27. Urbana, 1933.

The Volcanic Area of Bufumbira. Part I: Geology. By A. D. COMBE AND W. C. SIMMONS. Pp. 150, pls. 12, geologic map in color. Uganda Geol. Surv. Mem. III. Entebbe, 1933. Price, 15/. General geology and preliminary petrographical notes on one of the largest areas of leucite-bearing lavas (and therefore perhaps one of the largest potash reserves) in the world. Of particular interest to petrographers.

Investigations in Ceramics and Road Materials, 1930 and 1931. Pp. 175. Canada Dept. Mines, Mines Branch No. 726. Ottawa, 1933. Contains: Ceramic bodies for electrical heating devices, by L. P. COLLIN; Colour control of brick, by L. P. COLLIN; Roofing-tile clays and

shales of eastern Canada, by J. F. McMahon; The production of shapes from soapstone dust, by J. G. Phillips; Treatment of clays to overcome drying defects, by J. G. Phillips; Road gravels in Quebec, by R. H. Picher.

Caverns of Virginia. By W. M. McGill. Pp. 187, pls. 48, figs. 23, tables 4. Virginia Geol. Surv. Bull. 35, Educ. Ser. No. 1. University, Va., 1933. A comprehensive treatise, including also descriptions of all the famous caves in Virginia. Written for the layman, yet the author has not shunned technical matters, which he has introduced so skillfully that they are easily understandable. The excellence of his treatment is fittingly matched by the beautiful work of the publishers: hand-set type, heavy laid paper, and exceptionally fine plates.

Guidebook of the Western United States, Part F; Southern Pacific Lines. By N. H. Darton. Pp. 304, maps 29, pls. 49, figs. 71. U. S. Geol. Surv. Bull. 845. Washington, 1933. Price, $1. Town-by-town description along all the routes of this railroad, of the geography, history, economic geography, and geology, with special reference to the last. The abundance and excellence of the maps and illustrations are noteworthy.

A Survey of the High-Sulphur Crude Oils (Black Oils) Produced in Wyoming. By H. M. Thorne and W. Murphy. Pp. 56, figs. 3. U. S. Bur. Mines Tech. Paper 538. Washington, 1932. Price, 10c.

Ground Water in the Paleozoic Rocks of Northern Alabama. By W. D. Johnston, Jr. Pp. 414, figs. 54, pls. 23. Alabama Geol. Surv., Spec. Rpt. No. 16. Pt. I: Text. University, Ala., 1933. Geology, physiography, and ground water by counties.

Gold Deposits and Geologic Formations of Redding and Weaverville Quadrangles (California). By C. V. Averill and N. E. A. Hinds. Pp. 122, figs. 19, maps 2. California Div. of Mines, State Mineralogist's Rpt. XXIX. Sacramento, 1933.

Arizona Gold Placers and Placering. By E. D. Wilson, G. R. Fansett, et al. Pp. 148, figs. 15. Univ. of Arizona Bull. vol. IV, No. 6. (Bur. of Mines, Min. Tech. Ser. 35, No. 135.) Tucson, 1933. Occurrence, history, production, etc., and much valuable information for the novice on prospecting for, and recovery of, gold.

Prospecting for Placer Gold in South Dakota. By D. L. M. Anderson. Pp. 17, figs. 6. South Dakota Geol. Surv., Rpt. of Inves. No. 15. Vermilion, S. Dak., 1933. Hints for the novice.

Geologic History of Black Hills Gold Placers. By J. P. Connolly. Pp. 16, figs. 4. South Dakota Geol. Surv., Rpt. of Inves. No. 16, Vermilion, S. Dak., 1933. Anyone of limited geological knowledge and experience who intends prospecting for gold will find this paper of interest.

SCIENTIFIC NOTES AND NEWS

Sydney H. Ball, of New York City, is in Cuba on professional business.

Frank Ayer, manager of the Northern Rhodesia Roan Antelope mines, Luanshya, is now also directing the recently started production operations at Mufulira.

Donald C. Barton, of Houston, Texas, has joined the staff of the Humble Oil and Refining Company as consulting research geologist and geophysicist, with headquarters at Houston.

Sidney H. Haughton, formerly at Cape Town, South Africa, is now Director of the Geological Survey, Union of South Africa, at Johannesburg.

H. G. Turner, Director of Research for the Anthracite Institute, assisted by John L. G. Weysser, has completed studies of anthracite fields in the Middle West and South for the Coal Classification Committee of the American Standards Association.

Philip D. Wilson, formerly of the American Metal Company, is now with Pardners Mines Corporation, 230 Park Avenue, New York.

W. B. Heroy is now at 45 Nassau Street, New York, as chief geologist for the Consolidated Oil Corporation.

C. H. White is at Belgrade, Jugoslavia, engaged in investigating mining districts in the Balkans. He is also collaborating with Bohuslav Stoces on a textbook on Structural Geology with special reference to Economic Deposits, to be published shortly by Macmillan.

R. A. Pelletier, formerly in Northern Rhodesia, is now located in Johannesburg as a consulting geologist.

Alfredo I. Rodriguez, Berkeley, California, is now at Baguio, P. I., with the Atamok Goldfields Mining Company.

Oliver B. Hopkins, geologist for the Imperial Oil Company, Ltd., is on a trip to South America.

J. M. Forbes, of Montreal, has resigned as general manager of Siscoe Gold Mines and gone to East Africa to represent Hollinger Consolidated at the Kakamega gold field.

E. N. Pennebaker has completed an extended geological investigation near Mountain City, Nevada, for E. C. Congdon, Duluth, Minn., and is continuing his work as chief geologist for the Consolidated Coppermines Corporation near Ely, Nev.

J. A. Swart, formerly at Babbitt, Minn., with the Mesabi Iron Company, is now doing engineering work for the U. S. Geological Survey at Quartzite, Ariz.

H. Ries, of Cornell University, was honored with a life membership in the American Ceramic Society at its recent convention in Cincinnati, in recognition of his services as one of the founders of the Society.

C. C. Doyle, recently with the Cia. Minera de Penoles, Avalos unit, has entered the University of Arizona for graduate study.

J. B. Knaebel, of the U. S. Bureau of Mines, has gone to the Philippines to take charge of a gold property. His address is Box 817, Manila.

Francis Cameron, geologist for the Anaconda Copper Mining Company, has moved his headquarters from Toronto to Seattle, Wash.

M. G. Edwards, with the Shell Oil Company, of Los Angeles, has returned from an extended trip to the oil fields of Rumania and the headquarters of his company at the Hague.

C. E. Keep is at 8 Caroline Road, Moseley, Birmingham, England, after a trip to India in the interests of the Attock Oil Co. Ltd.

Dale L. Pitt, of the Premier Gold Mining Company, has been carrying on development work at the gold quartz property of the Alexandria Mining Company in the Phillips Arm section, Nanaimo mining division, 150 miles north of Vancouver, on which the Premier Company has an option.

The U. S. Geological Survey announces the first discovery of the potash mineral polyhalite in Kansas. It was found in Trigo County, four miles south of Riga, at a depth of 2,000 feet.

The Geological Society of Switzerland announces its fiftieth anniversary, to be celebrated by a geological convention in September, 1934. Excursions lasting ten to twelve days will start from the various university towns, to join in Lucerne on September 21, for an ascent of Mount Pilatus and a closing banquet. All geologists are invited to participate by the President of the Society, Maurice Lugeon, Laboratoire de Geologie, Université, Lausanne.

The scientific library of the late U. S. Grant, who was for thirty-three years head of the Department of Geology at Northwestern University, has been presented to the Department by Mrs. Grant, making an addition to the library of 1,500 bound and 4,000 unbound volumes.

The American Association of Petroleum Geologists will hold its 19th annual convention at Dallas, Texas, March 22–24, with headquarters at the Baker Hotel. Prospective papers should be sent in to F. H. Lahee, Box 2880, Dallas.

William Morris Davis, Professor of Geology at Harvard University from 1899 to 1912, died on February 5, in his eighty-fourth year.